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EVALUATION OF BALL ON THREE DISKS AS LUBRICITY EVALUATOR FOR CI/LI IN SYNTHETIC JP-5

April 2004

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WINNER OF THE 1995 PRESIDENTIAL AWARD FOR QUALITY

U.S. Army Tank-Automotive Research,
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Detroit Arsenal
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13. ABSTRACT ***(Maximum 200 Words)***
Synthetic fuel, like other poor lubricity fuels, will require lubricity-improving additives in order to prevent excessive engine fuel pump and injector wear. Lubricity improver additive, at minimum and maximum treat concentrations, were blended with a synthetic JP-5 hydrocarbon fuel containing no sulfur or aromatic species. The blends were then tested using the Ball on Three Disks (BOTD) bench-top test to determine their respective wear scars. Wear was determined to decrease in a non-linear fashion as the lubricity additive concentration increased. The BOTD has been shown to have correlative utilization over other diesel fuel lubricity bench-top tests including the Scuffing Load Ball on Cylinder Lubricity Evaluator (SLBOCLE) and High Frequency Reciprocating Rig (HFRR). The BOTD compares favorably with the lubricity additive qualification bench-top test (Ball on Cylinder Lubricity Evaluator [BOCLE]) because of its lubricity additive sensitivity; however, published data indicates that it can more adequately represent conditions found in fuel pumps.

14. SUBJECT TERMS
Lubricity, CI/LI additive, BOTD, BOCLE, SLBOCLE, HFRR, Rotary Pump Test, Synthetic JP-5, Fischer-Tropsch (F-T) Fuel, Gas-to-Liquid (GTL) Fuel

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EXECUTIVE SUMMARY

PROBLEMS AND OBJECTIVES

Fuel injection pumps components develop wear more rapidly when exposed to fuels with poor lubricity. Worn components may lead to degenerative performance and wear-induced premature pump failure. Poor lubricity fuels CAN be remedied to have satisfactory lubricity with the addition of lubricity-improving additives. The most accurate method of measuring the lubricity of a sample fluid is to use the Rotary Fuel Injection Pump Test Rig. The rig is sensitive to additive addition and is capable of detecting and distinguishing changes in lubricity. Although reliable and accurate, the rig is very expensive to operate costing $28,000 dollars for duplicate tests. In addition to the high cost, the test rig requires a great deal of expertise to operate and testing can be time consuming with up to 1000 hours of operation to failure. As a result, there has been much interest in developing an affordable, quick, and easy-to-use lubricity bench-top test that is sensitive to additives. The objective of this research was to: (1) determine the sensitivity of the Ball On Three Disks (BOTD) bench-top lubricity tester to military fuel corrosion inhibitor/lubricity improver (CI/LI) additive used in poor lubricity synthetic aviation turbine fuel, and (2) identify whether BOTD can detect lubricity improvement when CI/LI is blended at minimum and maximum treat levels with synthetic aviation turbine fuel, and (3) assess whether BOTD results correlate well with rotary fuel injection pump tests conducted at South West Research Institute (SwRI).

IMPORTANCE OF PROJECT

The development of an accurate and correlative bench-top lubricity tester will create an affordable alternative to the Rotary Fuel Injection Pump Test Rig. If successful, this BOTD method would provide a solution to the use of current bench-top lubricity tests that: (1) are not sensitive to additives, such as the Scuffing Load Ball on Cylinder Lubricity Evaluator (SLBOCLE) and High Frequency Reciprocating Rig (HFRR), and (2) are not representative of fuel pump conditions, such as the Ball on Cylinder Lubricity Evaluator (BOCLE). Additionally, having a lubricity bench-top test that reliably detects even minute amounts of CI/LI additive will support a minimum additization specification for synthetic fuels.

TECHNICAL APPROACH

The BOTD was procured and established in the laboratory using ASTM reference lubricity fluids. The current operating procedure was exercised using ceramic balls and metal disks to determine the sensitivity to ASTM reference fluids, synthetic turbine fuel, and for a known lubricity improver added to the synthetic fuel at minimum and maximum treat levels according to the QPL for MIL-PRF-25017F.

ACCOMPLISHMENTS

Lubricity improver additive, at minimum and maximum treat concentrations, was blended with a synthetic JP-5 hydrocarbon fuel containing no sulfur or aromatic species and produced via Gas-to-Liquids (GTL) technology utilizing Fischer-Tropsch (F-T) catalysis. The blends were then tested using the BOTD to determine their respective wear scars. This method did show some ability to detect the addition of CI/LI additive as determined through decreased wear scars, however not yet to an acceptable level of precision. Several areas were identified for further improvement and the recommendation was mad to continue the development of this BOTD method.

MILITARY IMPACT

Military turbine fuel (JP-8 and JP-5) requires the addition of CI/LI that is effective in reducing unacceptable wear in arctic designed rotary fuel pumps used in HMMWV vehicle diesel engines. These lubricity additives were previously not detectable in fuel using industry developed diesel bench-top lubricity tests. The BOTD has been shown to be sensitive to CI/LI-additized, poor lubricity synthetic JP-5 fuel. This lubricity bench test can be pursued for development into a standard test for use in fuel specifications. This technology may also be useful in developing specifications for use of other commercial lubricity additives that could than be introduced into military fuels.

FOREWORD / ACKNOWLEDGEMENTS

This work was performed during FY03 in the laboratories of the Petroleum and Water Business Area (PWBA), part of the Tank Automotive Research Development and Engineering Center (TARDEC) of the U.S. Army Tank-automotive and Armaments Command (TACOM) located in Warren, MI. The authors wish to thank the National Automotive Center and Herbert H. Dobbs for encouraging and funding this work. The authors gratefully acknowledge Kathryn S. Kline for her technical support in performing the BOTD testing.

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I. OBJECTIVE

The objective of this research was to determine the sensitivity of the Ball on Three Disks (BOTD) bench-top lubricity tester to military fuel corrosion inhibitor/lubricity improver (CI/LI) additive used in poor lubricity synthetic S-5 turbine fuel. For the purposes of this study, lubricity can be defined as: “The ability of a fuel to prevent or minimize wear in diesel fuel injection equipment." [1][1]. This lubricity bench-top test methodology is needed to develop lubricity additive specifications for synthetic fuels.

II. BACKGROUND

The most common bench-top test methods are Ball-On-Cylinder Lubricity Evaluator (BOCLE), Scuffing Load Ball-On-Cylinder Lubricity Evaluator (SLBOCLE), High-Frequency Reciprocating Rig (HFRR), and the Ball on Three Disks (BOTD). [1, 2, 4-9]. Past reports have shown that SLBOCLE and HFRR bench tests directionally correlate with field performance, but lack sensitivity to additives used at low concentration (i.e., 12 to 24 mg/L allowed by JP-8/JP-5 fuel specification). Although the SLBOCLE and HFRR directionally indicate the lubricity of the fuel, more work is needed to ensure that the lubricity improvements when using Corrosion Inhibitor/Lubricity Improver (CI/LI) additives are reflected in the results. Data for BOCLE and BOTD, along with the Low-Frequency Reciprocating Rig (LFRR) version of the HFRR, suggest that better bench test correlation to fuel rotary pump rig tests are achievable for CI/LI treated turbine fuels.

The U.S. Military has evaluated the lubricity effect of using the CI/LI additive. CI/LI is a carboxylic acid based material qualified under MIL-PRF-25017 and is required to be in JP-8/JP-5. [3,4] This evaluation was done with a “Rotary Fuel Injection Pump Test Rig” that used the same arctic-designed rotary fuel pumps fitted into HMMWVs. This effort compared neat Jet A-1 (JP-8 base fuel) fuels of different lubricity levels and the same fuels with the CI/LI additive. The results showed a dramatic increase of the number of hours that the rotary fuel pump was able to operate when the fuel was treated with CI/LI. For example, pumps using fuel without CI/LI additive were worn out at between 60-200 hours. The same base fuels treated with CI/LI additive completed 1000 hours of pump rig testing. At 1000 hours, the pumps had only minor changes in fuel delivery performance. However, the lubricity bench tests (SLBOCLE, HFFR) designed by industry to measure diesel fuel lubricity did not detect this change in fuel lubricity level between the untreated and treated turbine fuels.

The development of an accurate and correlative bench-top lubricity tester will create an affordable alternative to the Rotary Fuel Injection Pump Test Rig, which costs approximately $28,000 for each duplicate test. The rotary pump rig test requires a great deal of mechanical expertise and technical knowledge to operate and evaluate the results. In addition to cost savings, the bench-top lubricity test is smaller, easier to use, and produces results faster then the 1000 hour maximum failure time of the rotary pump rig test.

[1] Numbers in square brackets designate references listed in Section VII of this report.

The demand for an affordable and correlative bench-top lubricity test has increased due to the influx of low sulfur (and consequently poor lubricity) fuels into commercial fuel market. These low sulfur fuels will be produced to comply with increasingly stringent environmental policies focused on the reduction of sulfur and aromatics in automotive petroleum derived fuels. The reduction of aromatics and sulfur has led to numerous fuel refining technologies including improved hydro-treatment and sulfur extraction. Furthermore, gas-to-liquids (GTL) technology utilizing Fischer-Tropsch (F-T) catalysis to convert synthesis gas to liquid hydrocarbons under mild temperatures produces hydrocarbon fuels with essentially no sulfur or aromatics [2]. The military is interested in F-T fuel as a fuel cell reformer fuel and as an environmentally clean fuel for use in military vehicles. The synthetic F-T turbine fuel, S-5, made by Syntroleum for military evaluation contains less than 1 ppm sulfur and less than 1 percent aromatics. Although the low sulfur and low aromatic fuels will reduce emissions, they will have poor fuel lubricity. Fuel lubricity improver additives will be needed to improve lubricity to satisfactory levels. Bench-top lubricity tests provide an affordable alternative to measure the effectiveness of lubricity-improving additives to reduce rotary pump wear.

This report summarizes an effort to show the BOTD bench-top lubricity test can measure the lubricity of synthetic turbine fuel, S-5, and S-5 treated with CI/LI at concentrations shown to reduce rotary pump wear in pump test rigs. The BOTD is also of interest due to smaller size and cost of operation compared to the BOCLE tests. The BOTD instrument uses a test fluid to lubricate a rotating ceramic ball that is pressed against three disks by way of a load arm. [1, 6, 7] At the surface between the ceramic ball and the three disks, a wear scar is developed and becomes increasingly larger for poor lubricity fuels. A picture of the BOTD components is shown in Figure 1.

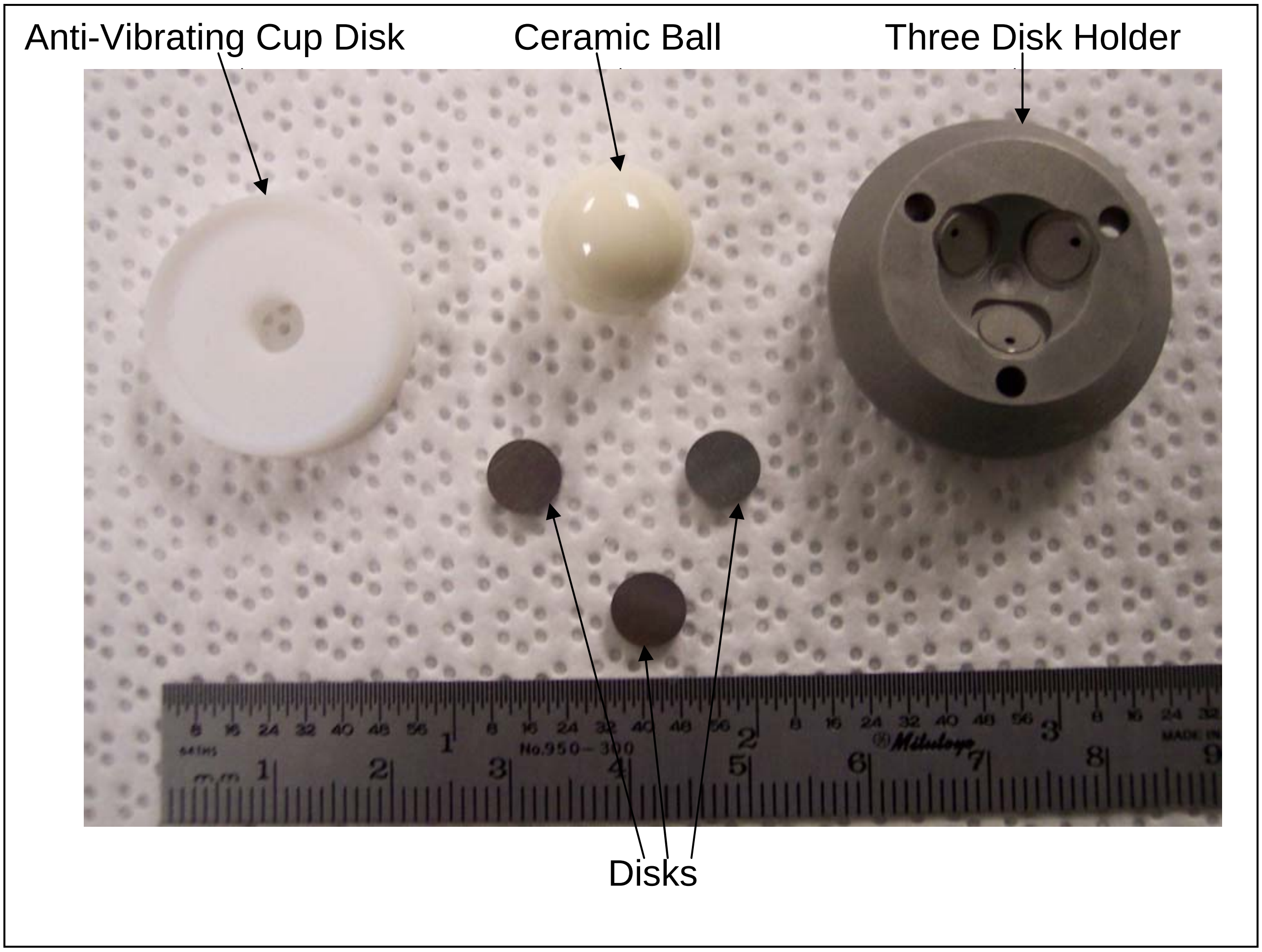


Figure 1. BOTD components

III. APPROACH

A synthetic fuel S-5, which contains zero sulfur and no aromatics, will be tested for lubricity. Pure S-5 is tested to determine the resulting wear scar representing baseline lubricity. Blends of S-5 with various concentrations of lubricity additive will be prepared and tested for lubricity. The BOTD will be utilized to measure lubricity and results compared to results from other lubricity detecting instruments like BOCLE, SLBOCLE, and HFRR.

The BOTD test method currently under development by ASTM provides a measure of lubricity by measuring the amount of wear that develops from contact by a rotating ½-inch ceramic ball pressed at a fixed load against three ¼-inch disks immersed in test fluid. Thus, during the 45-minute test, the better the lubricity, the less wear is developed on the three disks. Development of wear is measured and reported as wear scar diameter. The BOTD test conditions are listed in Table 1.

Table 1 • BOTD Test Conditions

Test Parameter	Value
Load	2.500 kg +/- 0.02 kg
Speed	60.0 RPM +/- 0.2 RPM
Test Duration	45 minutes +/- 1 sec
Temperature	Room Temperature (24° +/- 3°C)
Wear	Average wear scar diameter of the three disks
Humidity	45% +/- 5 % Relative Humidity
Fluid Volume	30 mL

Five samples were prepared and tested:

1. Fluid A: Good lubricity fluid
2. Fluid B: Poor lubricity fluid – IsoPar M
3. Pure S-5, untreated synthetic F-T fuel containing low sulfur and aromatics
4. S-5 + 12.0 mg/L Corrosion Inhibitor/Lubricity Improver (CI/LI) (MIL-PRF-25017F)
5. S-5 + 22.5 mg/L CI/LI

Fluids A and B are American Society for Testing and Materials (ASTM) reference samples known for their good and poor lubricity characteristics, respectively. Shown in Table 2 are lubricity values for these reference fluids as reported by ASTM.

Table 2 • Lubricity Values per ASTM for Reference Fluids

Test Description	***Average Result***	***Lower Acceptance***	***Higher Acceptance***
High-Frequency Reciprocating Rig (ASTM D 6079)			
HFRR at 60°C, wear scar diameter (μm)			
Fluid A, Lot 2-Reference Period 03/05/02 - 09/05/03	0.37	0.34	0.41
Fluid B, Lot 2-Reference Period 03/05/02 - 09/05/03	0.66	0.59	0.73
Scuffing Load Ball-on-Cylinder (ASTM D 6078)			
SLBOCLE, load (g)			
Fluid A, Lot 2-Reference Period 03/05/02 - 09/05/03	5593	5072	6115
Fluid B, Lot 2-Reference Period 03/05/02 - 09/05/03	1657	1257	2056

Reference Fluids A & B were tested in this evaluation to gauge the development of wear scars for fluids with comparable lubricity ratings. Pure S-5 was tested to provide a baseline assessment of the fuel's lubricity, and the wear scar measurements compared to Fluid A and B to determine its initial rating. After a baseline was established, CI/LI was blended with the fuel at 12.0 and 22.5 mg/L concentrations and tested to determine the effect on the development of wear scars. Each sample was tested at least three times to determine the reproducibility of the wear scars using the BOTD. The CI/LI selected for this work (coded FL-11761-03) was the same additive used in rotary pump rig tests and is considered to be a good lubricity additive compared to some (possibly better responding) approved CI/LI additives qualified to meet the specification. The minimum treat rate for a particular additive product qualification is additive package dependant and is shown in the Qualified Product List (QPL) for the specification. The minimum effective concentration is based on BOCLE testing whereas the maximum allowable concentration is based on allowable water separation test results.

IV. RESULTS

The lubricity-testing program was divided into three separate testing phases: reference fluids, baseline, and S-5 plus additive concentration level.

During testing, all of the test conditions were maintained, monitored, and recorded. The wear scars developed on the three disks were measured as described by BOTD procedure dated 2000 provided by the instrument manufacturer. The mean average of the wear scar and the standard deviation was calculated.

A. Reference Fluids

Two reference fluids designated Fluid A and Fluid B, with known good and poor lubricity characteristics, respectfully, were tested to determine average wear scar values. The resulting average wear scar, shown below in Table 3, will be used to gauge the lubricity of unknown fluids.

Table 3 • BOTD Wear Scars of Reference Fluids

	Fluid A - Good Lubricity		Fluid B - Poor Lubricity	
Run #	Mean Scar* (µm)	Std. Dev.** (µm)	Mean Scar* (µm)	Std. Dev.** (µm)
1	366	68	722	20
2	369	70	630	71
3	426	4	608	33
4	n/a	n/a	621	8
5	n/a	n/a	696	31
6	n/a	n/a	586	95
7	n/a	n/a	649	40
Average	***387******	***34*******	***645******	***49*******

* Mean Scar: mean of wear scars for three disks
** Standard Deviation: standard deviation from the mean scar
*** Average Mean Scar: average of mean scars reported
**** Average Standard Deviation: deviation of mean scars from the average mean scar

B. Baseline S-5 and Additives in S-5

Baseline testing of S-5 was performed to characterize lubricity before the testing of additives in S-5. The results of the baseline test are shown in Table 4.

S-5 fuel samples were blended to have a lubricity additive concentration of 12.0 mg/L, the minimum treatment level, and the maximum treatment level of 22.5 mg/L. The results of the BOTD tests are shown in Table 4.

Table 4 • BOTD Wear Scars for S-5 and S-5 Plus Additives

	S-5 (Baseline)		**S-5 + 12.0 mg/L CI/LI**		**S-5 + 22.5 mg/L CI/LI**	
Run #	Avg. Scar (µm)	Std. Dev. (µm)	Avg. Scar (µm)	Std. Dev. (µm)	Avg. Scar (µm)	Std. Dev. (µm)
1	815	6	553	95	557	34
2	740	63	698	24	622	30
3	802	17	696	22	592	25
Average	***786***	***40***	***649***	***83***	***590***	***33***

V. DISCUSSION

A. Reference Fluids

The two reference fluids were tested to determine the approximate wear scar that would develop for good and poor lubricity fuels. Fluid A, the good lubricity fluid, produced an average wear scar of 387 µm and an average standard deviation of 34 µm. Thus, we would expect other good lubricity fluids to produce wear scars approximately equal to 387 µm. Fluid B, the poor lubricity fuel, produced significantly larger wear scars averaging 645 µm with an average standard deviation of 49 µm for seven runs.

The BOTD gave individual disk wear scar results with high precision. For an individual run, the precision is measured by the standard deviation. The standard deviations in Fluid B for individual runs ranged from 95 µm to 8 µm meaning some runs were able to reproduce similar wear scars, while on others they deviated dramatically amongst the three disks. For Fluid A, the standard deviations per test run were 68 µm, 70 µm, and 4 µm, the maximum scar of the nine disks was 458 µm and a minimum scar of 282 µm. These large deviations make it difficult to determine the relative lubricity characteristic of each fluid. The published data for the BOTD suggests that a good lubricity fuel will have a wear scar diameter of less than 500 µm.

B. Baseline

The baseline results indicate that pure S-5 is a very poor lubricity fuel since the average wear scar of 786 µm is larger then that of Fluid B (645 µm), a known poor lubricity fuel. The average standard deviation obtained on Fluid B was 49 µm. Therefore, the 786 µm reflects a fuel with a poorer lubricity than Fluid B.

C. Additive Concentration: S-5 + Additive (CI/LI)

The relationship between lubricity improver additive concentration and wear scar development appears to be non-linear as shown by the trend line in Figure 2.

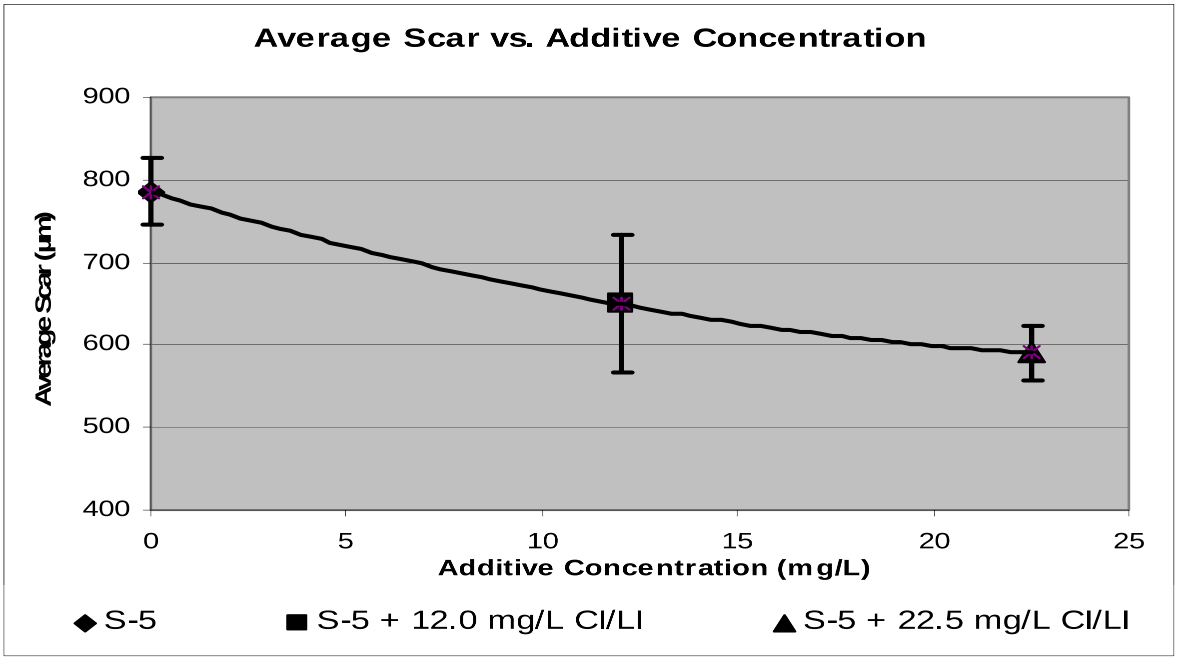


Figure 2. Average Wear Scar versus Additive Concentration

The addition of lubricity improver additive to S-5 does appear to improve the lubricity of the fuel as evidenced by the decrease in average wear scar. More significantly, rotary pump test rig results determined in an associated testing program completed at Southwest Research Institute, showed a marked improvement in S-5 fuel lubricity with the addition of CI/LI. Two rotary injection pumps running with untreated S-5 had to be shutdown well short of the 500 hour standard test duration due to premature wear. Pump tests with S-5 treated at the minimum CI/LI concentration did run to 500 hours with some indications of wear found; pump tests using S-5 treated at the maximum concentration of CI/LI also ran to 500 hours with little indications of wear found. These rotary injection pump test results, along with the results from this BOTD evaluation and other various bench-top lubricity tests completed in an associated testing program, are summarized in Table 5.

Table 5 • Results from Various Lubricity Evaluations

		S-5 (synthetic JP-5 fuel)		
Test Description	***ASTM Test Method***	***untreated***	***+12 mg/L C.I. (min. C.I.)***	***+22.5 mg/L C.I. (max. C.I.)***
High-Frequency Reciprocating Rig HFRR at 60°C, wear scar diameter (µm)	D 6079	629	662	668
Scuffing Load Ball-on-Cylinder SLBOCLE, load (g)	D 6078	975	1450	1333
Ball-on-Cylinder BOCLE, wear scar diameter (mm)	D 5001	0.95	0.76	0.68
Ball-on-Three-Disks BOTD, wear scar diameter (mm)	(Not approved) dated 09/00	0.786	0.649	0.59
Rotary Pump Testing test hours for pump 1, pump 2	similar to D 6898	96.5, 150.7	500, 500	500, 500

Notes

(1) ASTM D 6079 repeatability is 80 micrometers
(2) ASTM D 6078 repeatability is 900 g
(3) Corrosion Inhibitor listed per QPL-25017-19, qualified under MIL-PRF-25017F
(4) HFRR, SLBOCLE, and BOCLE test results per Ed Frame at SwRI, 3/31/03

The data in Table 5 indicates that the HFFR method did not detect any change in the lubricity of the fuel, while the SLBOCLE, with results within established repeatability, showed a trend towards improvement when the additive was added. However, the SLBOCLE did not detect differences in fuel lubricity improvements between minimum and maximum concentrations of CI/LI. The BOCLE and the BOTD showed improvements in fuel lubricity at both additive concentrations. A previously suggested minimum limit for BOTD was 0.440-0.50 mm. [2] The data reported in Table 5 suggests that for Army Arctic pumps the maximum limit for BOTD could be 0.60-0.65 mm as correlated to satisfactory performance in rotary pump testing.

VI. CONCLUSION AND RECOMMENDATIONS

The S-5 synthetic fuel with low sulfur and aromatics produced larger wear scars than ASTM Fluid B, a known poor lubricity fluid. The addition of lubricity improver additive, evaluated in S-5 at two different concentrations, was detected by both the BOCLE and the BOTD. However, for the BOTD, the high degree of variability among wear scars measured on the three disks in several of the individual runs leaves room for improvement of this apparatus, test method, or both.

It is recommended that the BOTD apparatus, operating conditions and testing methodology be further investigated in an effort to improve the viability of this technique as a bench top test method for screening lubricity improver additives. Future testing should be conducted utilizing disks with polished surfaces in an attempt to reduce the variability in wear scars for an individual run and to increase sensitivity. Also, testing should incorporate the use of steel balls in addition to the current ceramic balls, as the steel balls are more readily available as a commercially available repeatable product, compared to the ceramic balls that are purported to be difficult to produce in reproducible batches.

In the current methodology, the disk holder cup is placed into position manually. Consideration should be given to use of a hydraulically-controlled arm to raise the cup into position as another means of reducing test variability. Other possible contributors to variability should be assessed by investigating: (1) variation of cup test temperature and ullage humidity and (2) pre-rinse or equilibrium of test cup with test fluid prior to final fill.

Finally, this evaluation was completed with just a single CI/LI per QPL-25017-19. Future work should look at other approved CI/LI additives, particularly to see if others may be more effective in the synthetic fuel using the BOTD and BOCLE testers.

VII. REFERENCES

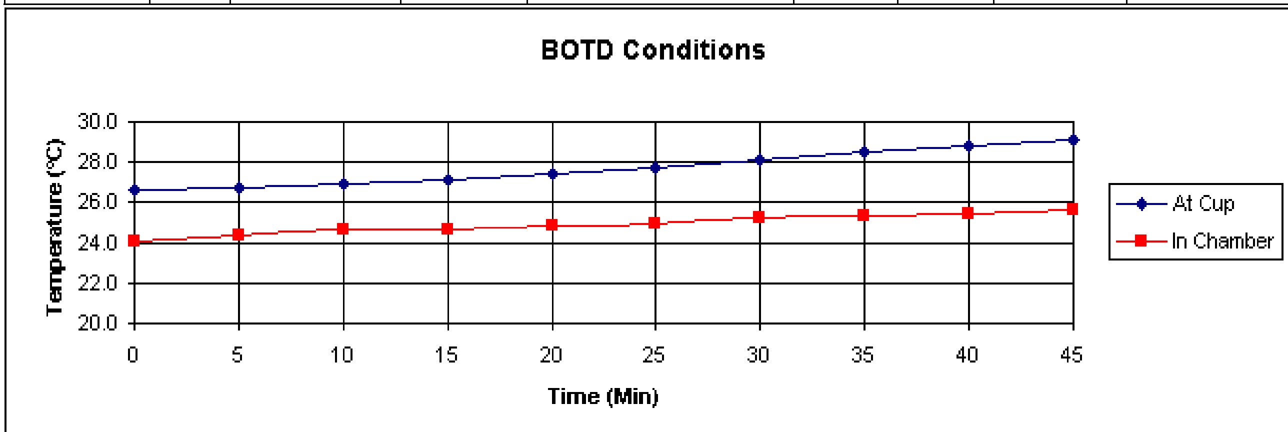
1. Gray, Clint, Aaron Wilcox, Michael Scott and Gary Webster, (Advanced Engine Technology Ltd.), "Investigation of Diesel Fuel Lubricity and Evaluation of Bench Tests to Correlate with Medium and Heavy Duty Diesel Fuel Injection Equipment Component Wear - Part I", SAE Paper No. 2002-01-1700, 2002.
2. Stavinoha, Leo L., Emilio S. Alfaro, Herbert H. Dobbs, Jr., Luis A Villahermosa, and John B. Heywood, "Alternative Fuels: Gas to Liquids as Potential 21st Century Truck Fuels", SAE Paper No. 2000-01-3422, 2000.
3. MIL-PRF-25017F, Military Specification, Revision Level F, "Inhibitor, Corrosion/Lubricity Improver, Fuel Soluble", Prepared by the Aeronautical Systems Center, Issue Date 10 Nov 97.
4. Alvarez, Ruben A. and Edwin A. Frame, "Component Time to Failure Using Jet A/Jet A-1", DESC Contract No. SP060099D5944, SwRI Contract No. 03.40.50.04352, Southwest Research Institute, Engine and Vehicle Research Division, Fuels and Lubricants Technology Department, June 2002.
5. Frame, Edwin A., Howard W. Marbach, Jr., Kenneth H. Childress, Douglas M. Yost, and Steven R. Westbrook, Operability and Compatibility Characteristics of Advanced Technology Diesel Fuels, Final Report, SWRI Project No. 03-02476, CRC Project No. AVFL-2, Coordinating Research Council, Inc., Southwest Research Institute, Division of Engine and Vehicle Research, Fuels and Lubricants Technology Department, , January 2002.
6. Valatie, Robert M., and Ning Ren (Falex Corp.), "Diesel Fuel Lubricity by Standard Four Ball Apparatus Utilizing Ball on Three Disks, BOTD", SAE Paper No. 950247, 1995.
7. Valatie, Robert M., (Falex Corp.), "Diesel Fuel Lubricity BOTD Status – 1995", SAE Paper No. 952371, 1995.
8. Nikanjam, Manuch, "Diesel Fuel Lubricity: On the Path to Specifications", SAE Paper No. 1999-01-1479, 1999.
9. Nikanjam, Manuch, Paul Henderson, Paul Lacey, Rinaldo Caprotti, Dean Simeroth, and Ken Mitchell, "Diesel Fuel Lubricity", F&L Asia, Inc, 2002.

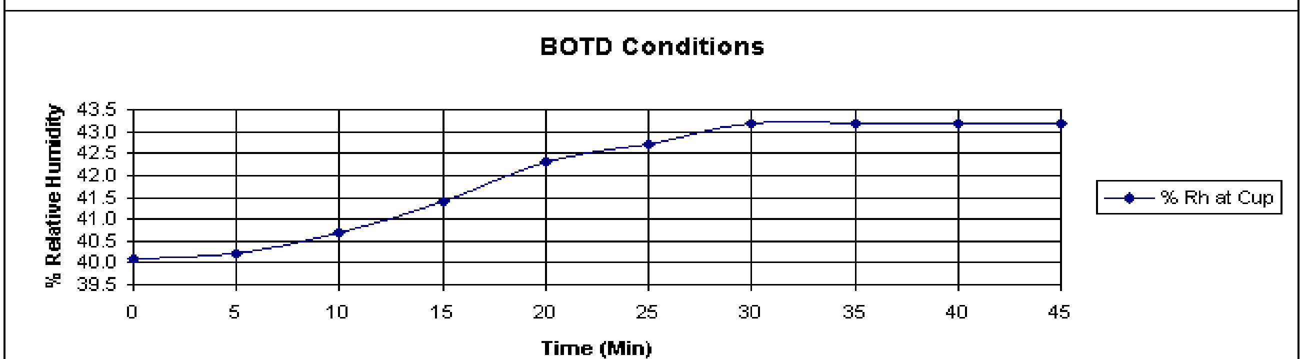
APPENDICES

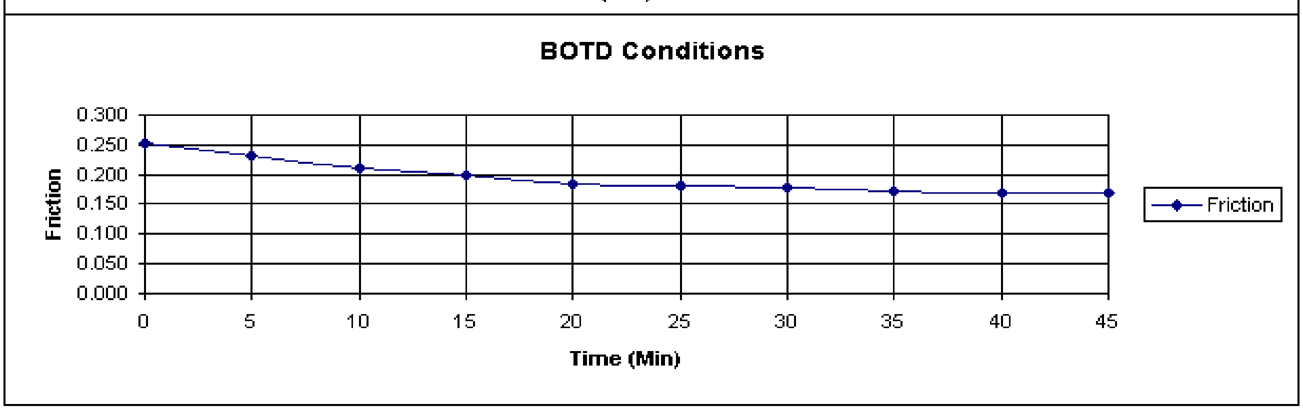
APPENDIX A

Data Sheets for Fluid A

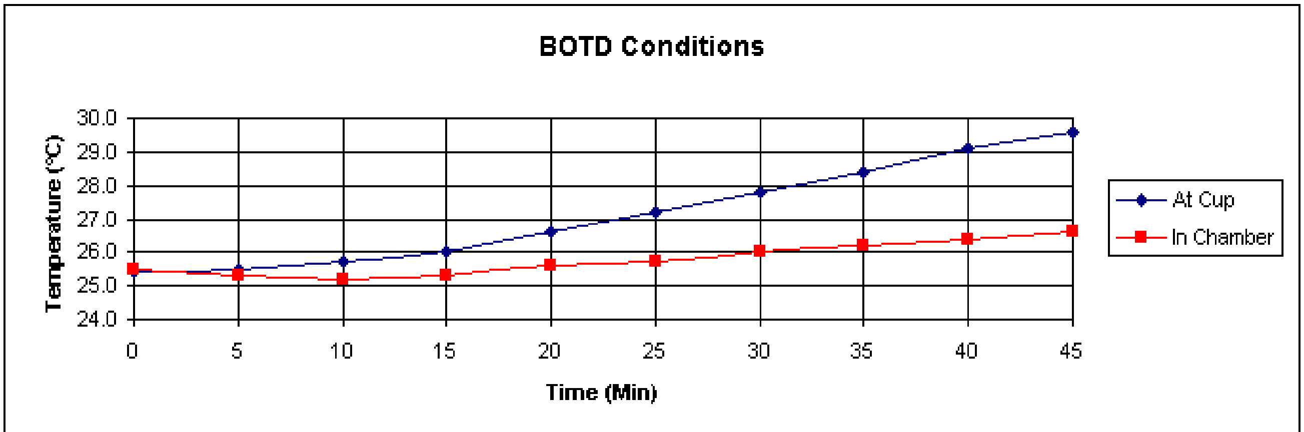
BOTD Data and Charts								
Sample ID:	Fluid A (FL-11763-03)			Run 1, Cup 1		**Date:**	18-Sep-03	
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**			**Average per Disk**
0	40.1	26.6	0.251	24.1		**µm**	**µm**	**µm**
5	40.2	26.7	0.232	24.4	Disk 1	282	289	286
10	40.7	26.9	0.212	24.7	Disk 2	440	434	437
15	41.4	27.1	0.199	24.7	Disk 3	380	373	377
20	42.3	27.4	0.185	24.9				
25	42.7	27.7	0.182	25.0	**Avg.**	366	**µm**	
30	43.2	28.1	0.178	25.2	**Std. Dev.**	68	**µm**	
35	43.2	28.5	0.173	25.3				
40	43.2	28.8	0.170	25.4				
45	43.2	29.1	0.168	25.6				

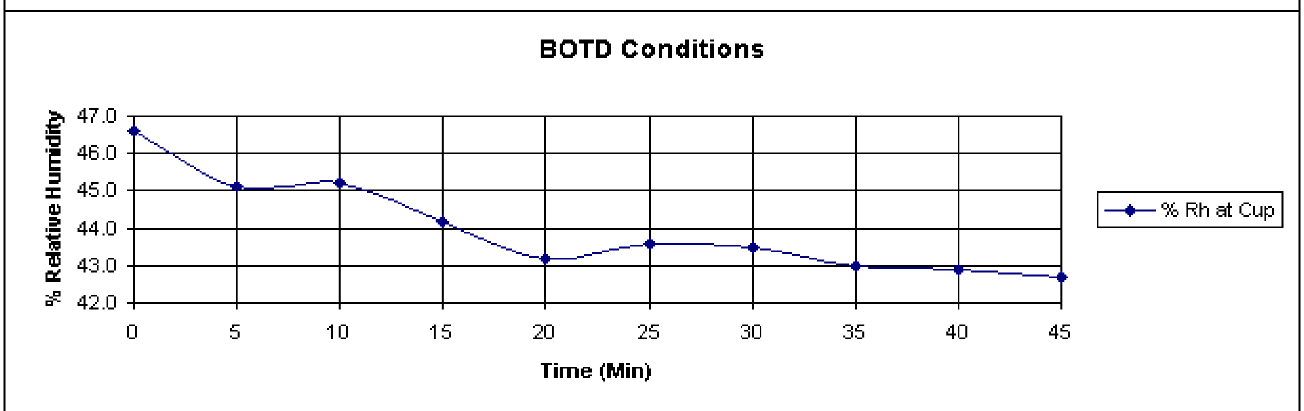


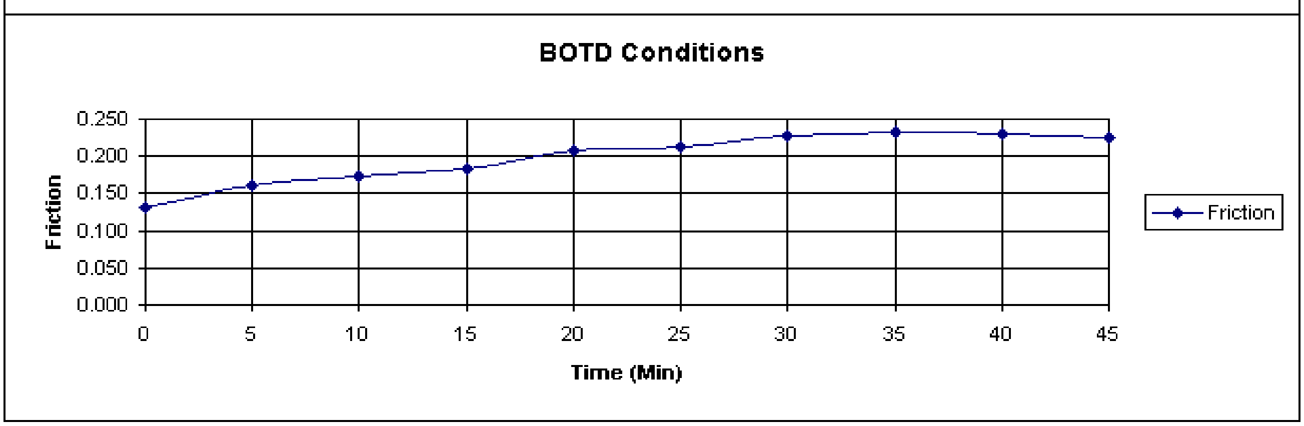




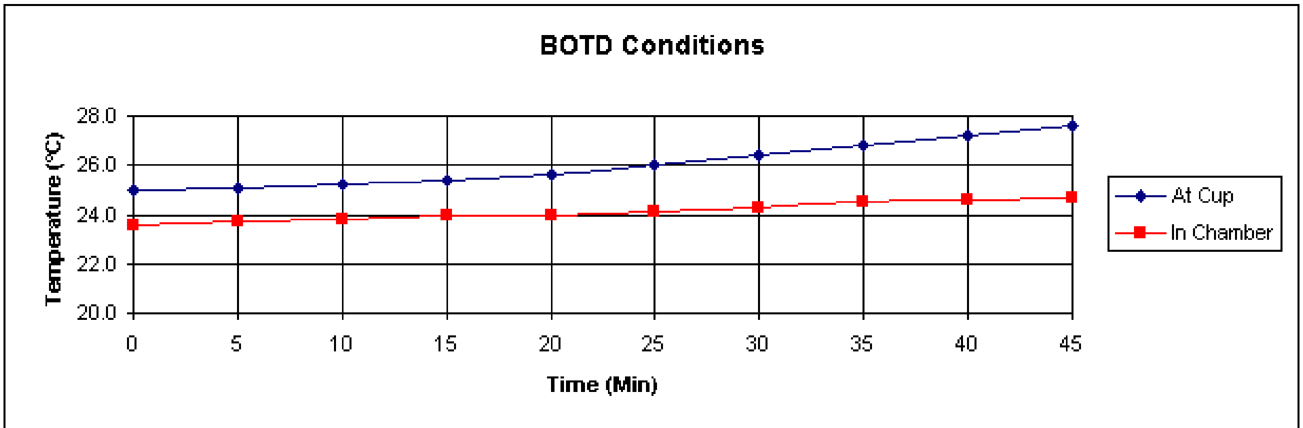
Sample ID:	Fluid A (FL-11763-03)			Run 2, Cup 1			Date:	9-Oct-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements				Average per Disk
0	46.6	25.4	0.130	25.5		µm	µm		µm
5	45.1	25.5	0.162	25.3	Disk 1	316	311		314
10	45.2	25.7	0.173	25.2	Disk 2	334	336		335
15	44.2	26.0	0.183	25.3	Disk 3	458	458		458
20	43.2	26.6	0.207	25.6					
25	43.6	27.2	0.213	25.7	Avg.	369	µm		
30	43.5	27.8	0.227	26.0	Std. Dev.	70	µm		
35	43.0	28.4	0.233	26.2					
40	42.9	29.1	0.230	26.4					
45	42.7	29.6	0.226	26.6					

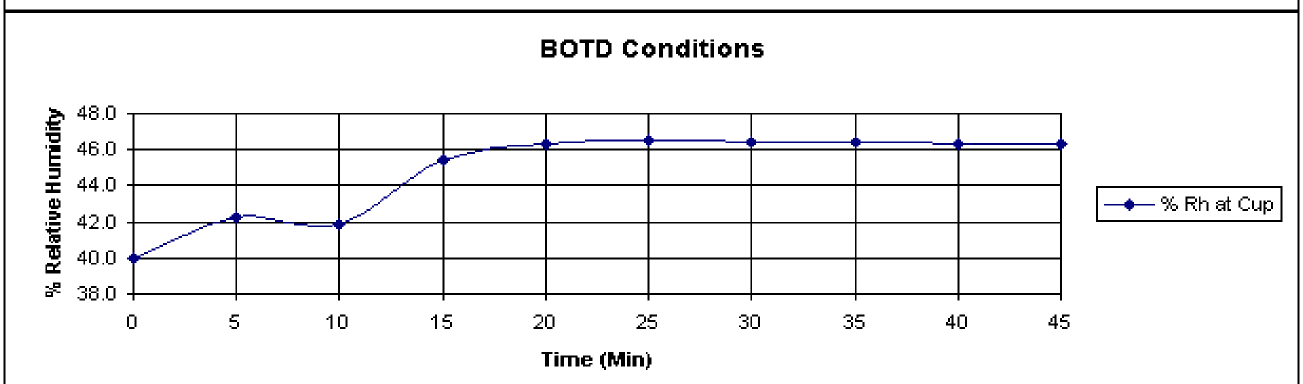


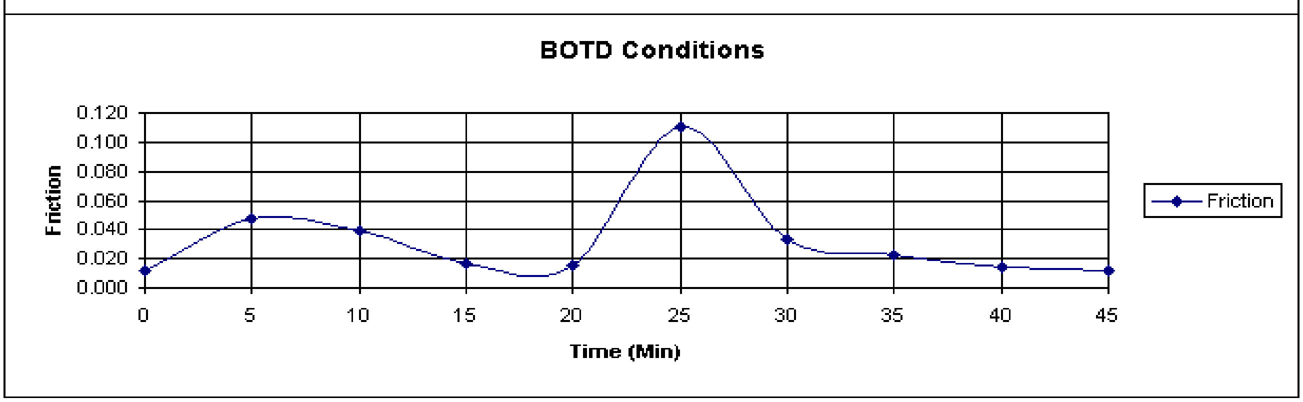




Sample ID:	Fluid A (FL-11763-03)			Run 3, Cup		Date:		
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**			**Average per Disk**
0	40.0	25.0	0.012	23.6		**µm**	**µm**	**µm**
5	42.3	25.1	0.048	23.7	Disk 1	423	419	421
10	41.9	25.2	0.039	23.8	Disk 2	430	428	429
15	45.4	25.4	0.017	24.0	Disk 3	430	428	429
20	46.3	25.6	0.015	24.0				
25	46.5	26.0	0.110	24.1	**Avg.**	426	**µm**	
30	46.4	26.4	0.033	24.3	**Std. Dev.**	4	**µm**	
35	46.4	26.8	0.022	24.5				
40	46.3	27.2	0.014	24.6				
45	46.3	27.6	0.012	24.7				



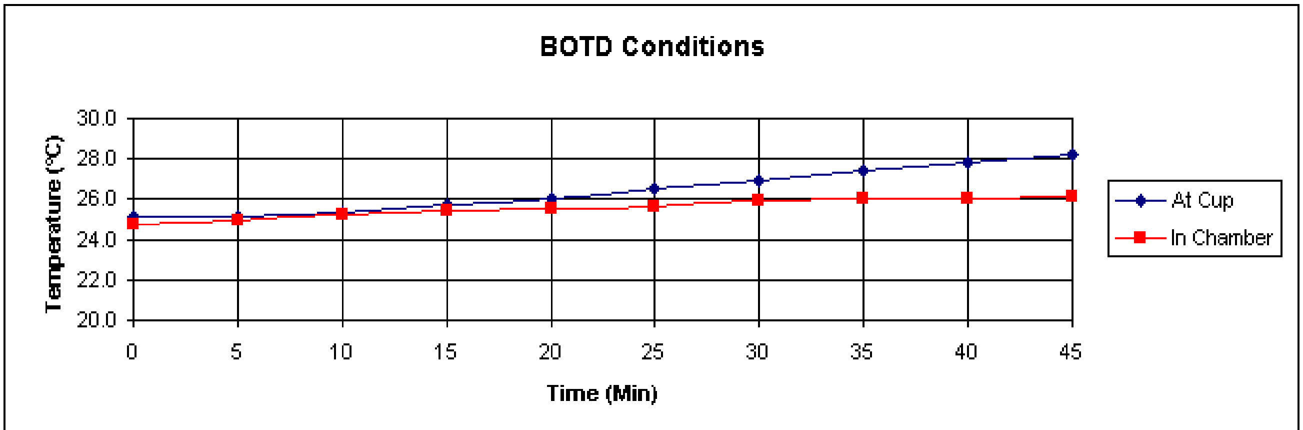


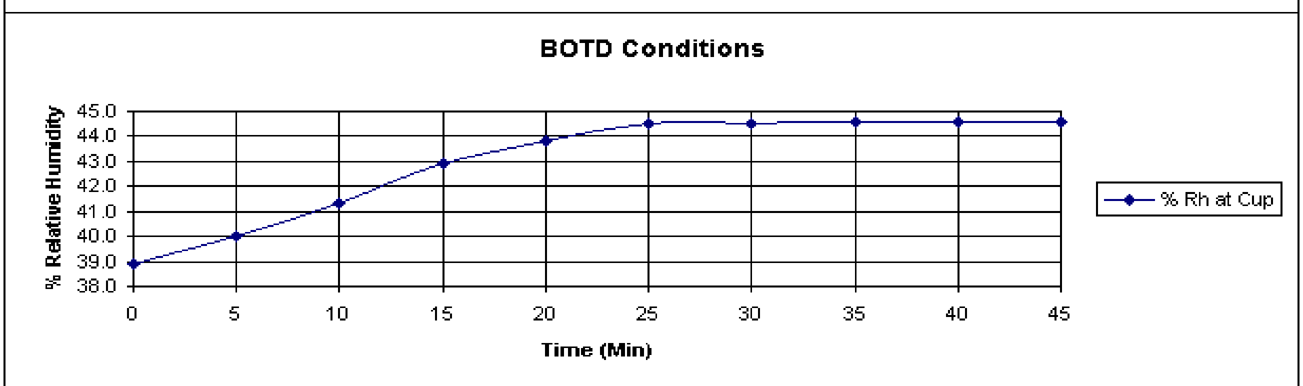


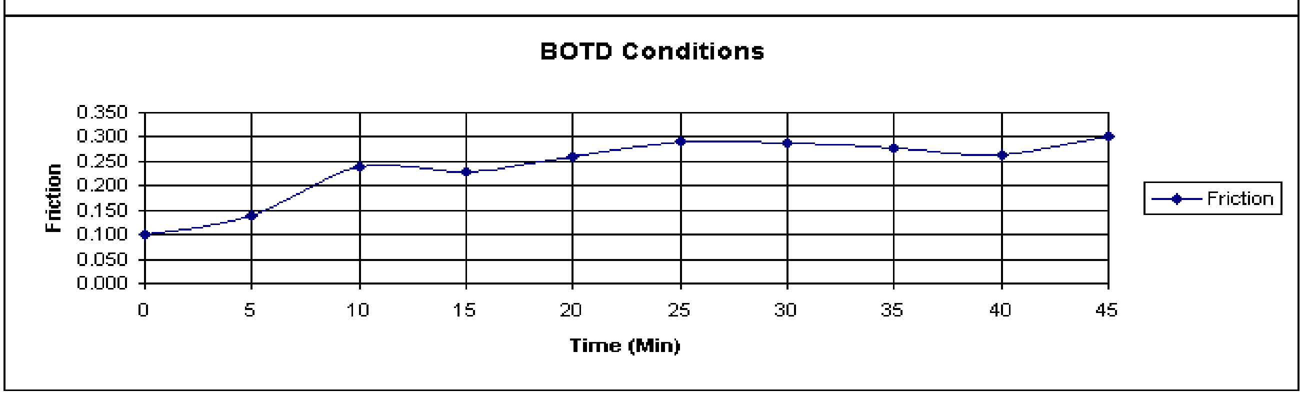
APPENDIX B

Data Sheets for Fluid B

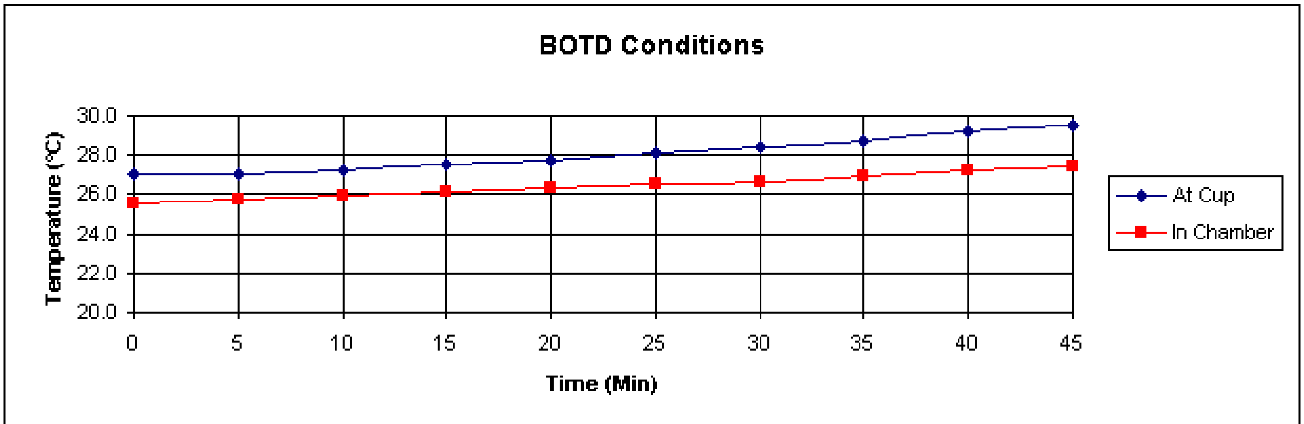
Sample ID:	Fluid B (FL-11762-03)			Run 1, Cup 1		Date:	25-Jul-03	
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**		**Disk Measurements**		**Average per Disk**
0	38.9	25.1	0.100	24.8		**µm**	**µm**	**µm**
5	40.0	25.1	0.140	25.0	Disk 1	707	703	705
10	41.3	25.3	0.240	25.2	Disk 2	No Scar	No Scar	N/A
15	42.9	25.7	0.230	25.4	Disk 3	738	740	739
20	43.8	26.0	0.260	25.5				
25	44.5	26.5	0.290	25.7	**Avg.**	722	**µm**	
30	44.5	26.9	0.288	25.9	**Std. Dev.**	20	**µm**	
35	44.6	27.4	0.276	26.0				
40	44.6	27.8	0.263	26.0				
45	44.6	28.2	0.301	26.1				

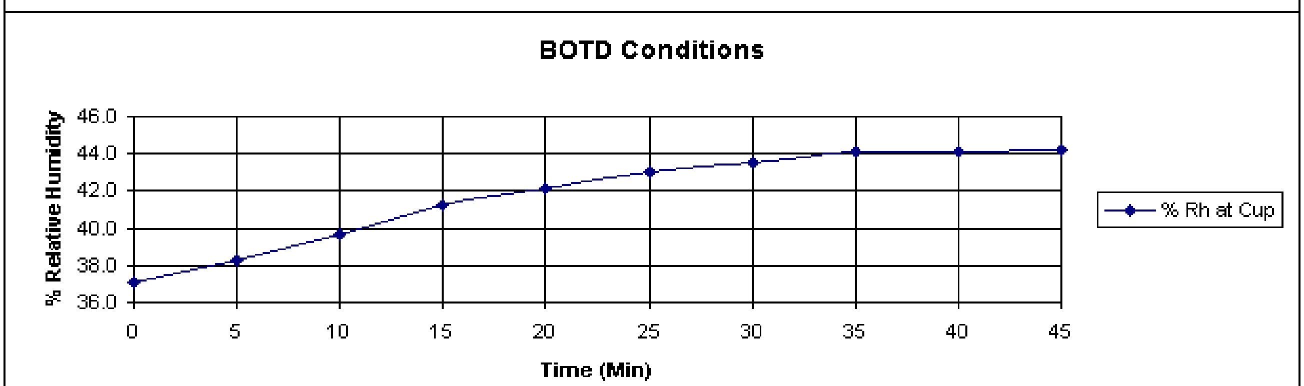


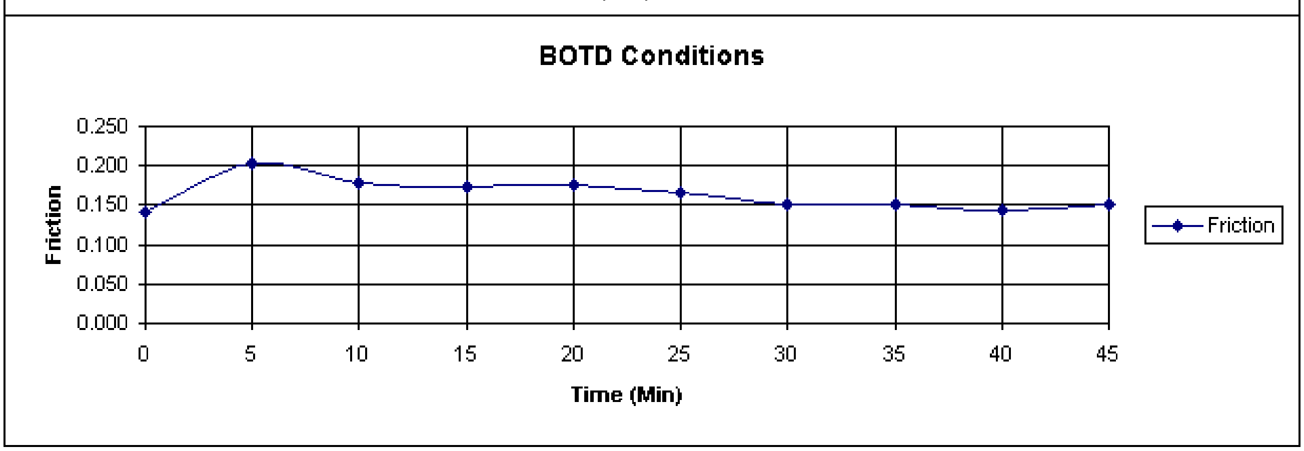




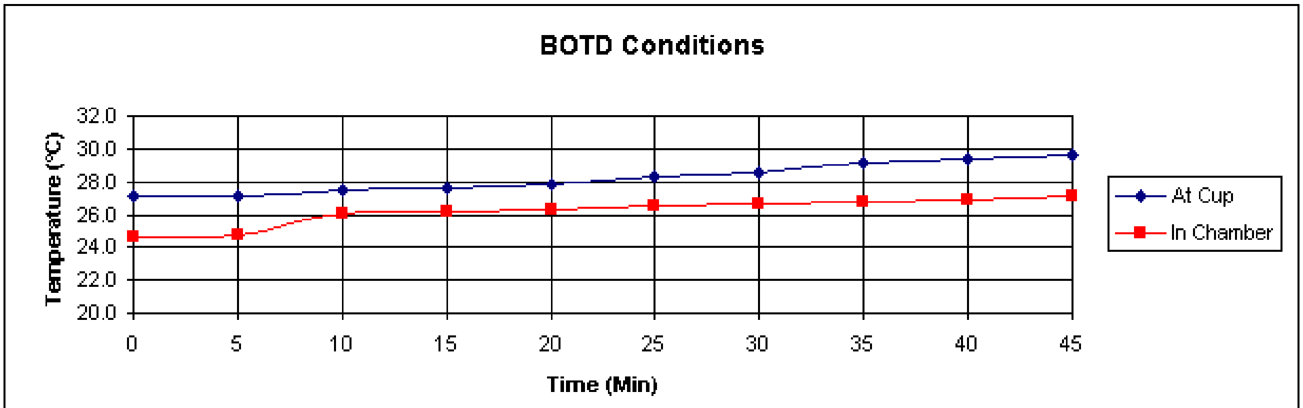
Sample ID:	Fluid B (FL-11762-03)			Run 2, Cup 2		**Date:**	25-Jul-03	
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**			**Average per Disk**
0	37.1	27.0	0.140	25.5		**µm**	**µm**	**µm**
5	38.3	27.0	0.202	25.7	Disk 1	560	557	559
10	39.7	27.2	0.177	25.9	Disk 2	716	716	716
15	41.2	27.5	0.173	26.1	Disk 3	613	617	615
20	42.1	27.7	0.175	26.3				
25	43.0	28.1	0.167	26.5	**Avg.**	630	**µm**	
30	43.5	28.4	0.152	26.6	**Std. Dev.**	71	**µm**	
35	44.1	28.7	0.150	26.9				
40	44.1	29.2	0.143	27.2				
45	44.2	29.5	0.150	27.4				

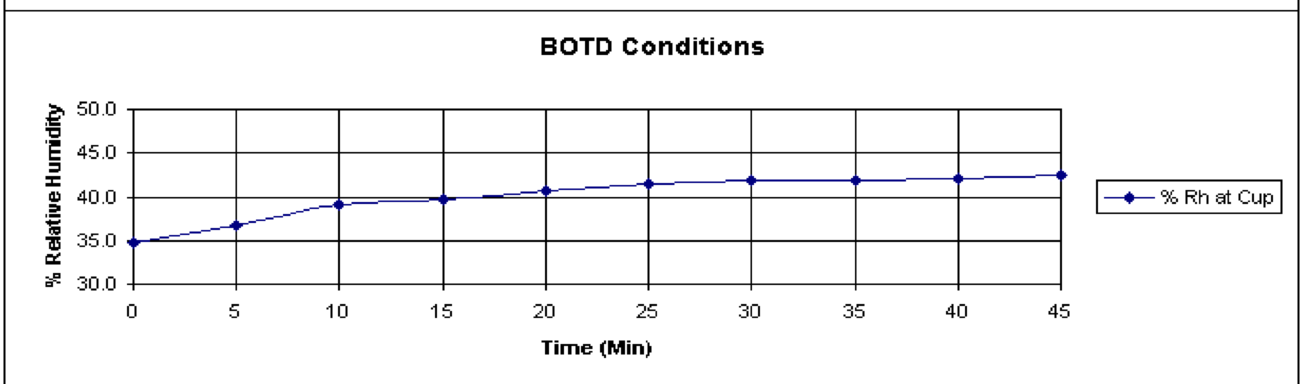


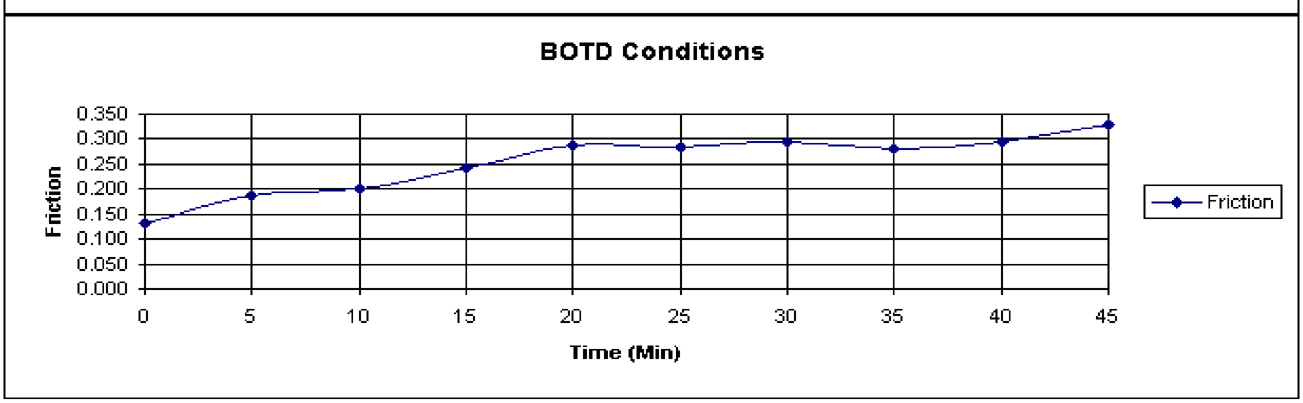




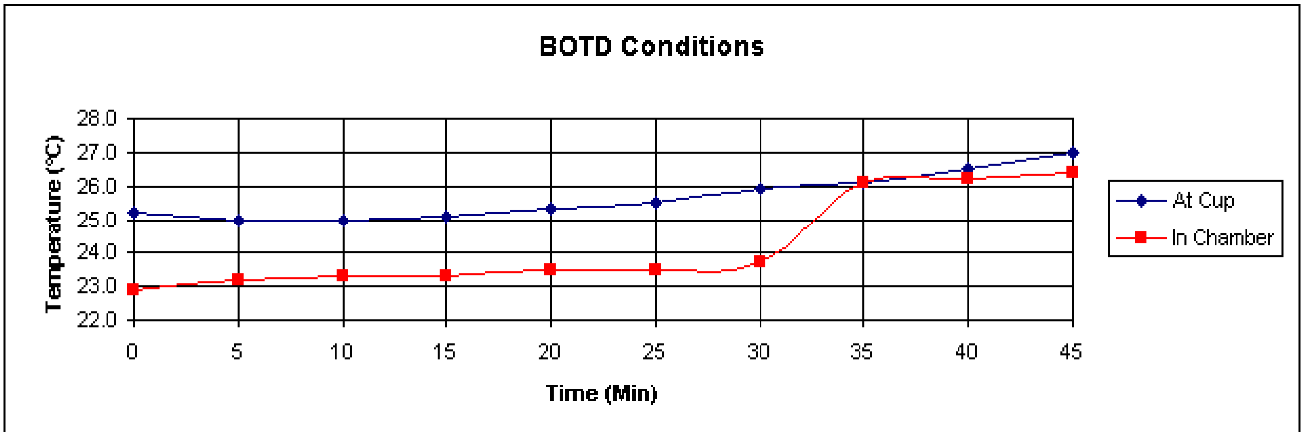
Sample ID:	Fluid B (FL-11762-03)			Run 3, Cup 3		Date:	28-Jul-03	
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**			**Average per Disk**
0	34.8	27.1	0.130	24.6		**µm**	**µm**	**µm**
5	36.7	27.1	0.188	24.7	Disk 1	631	635	633
10	39.1	27.5	0.202	26.1	Disk 2	626	622	624
15	39.8	27.6	0.242	26.2	Disk 3	569	562	566
20	40.7	27.9	0.288	26.3				
25	41.5	28.3	0.284	26.5	**Avg.**	608	**µm**	
30	41.8	28.6	0.295	26.6	**Std. Dev.**	33	**µm**	
35	41.9	29.1	0.281	26.8				
40	42.1	29.4	0.293	26.9				
45	42.4	29.6	0.328	27.1				

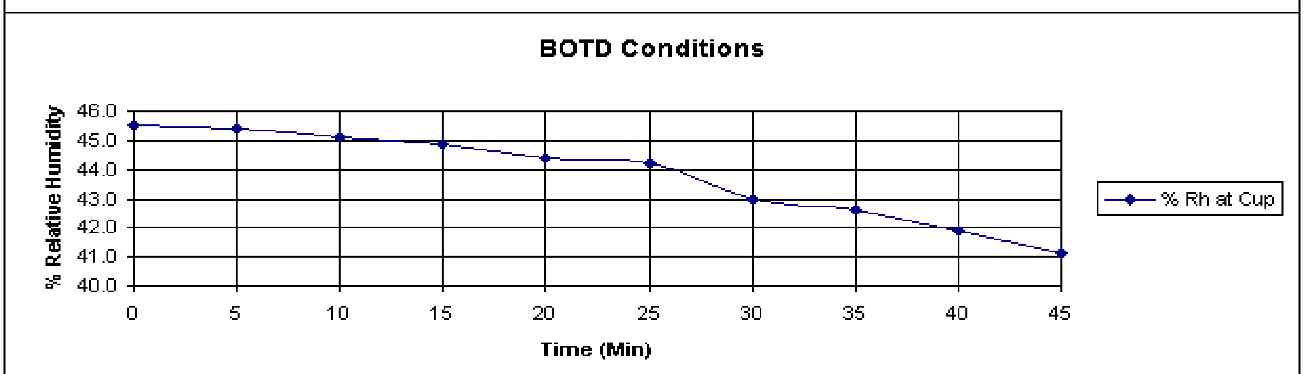


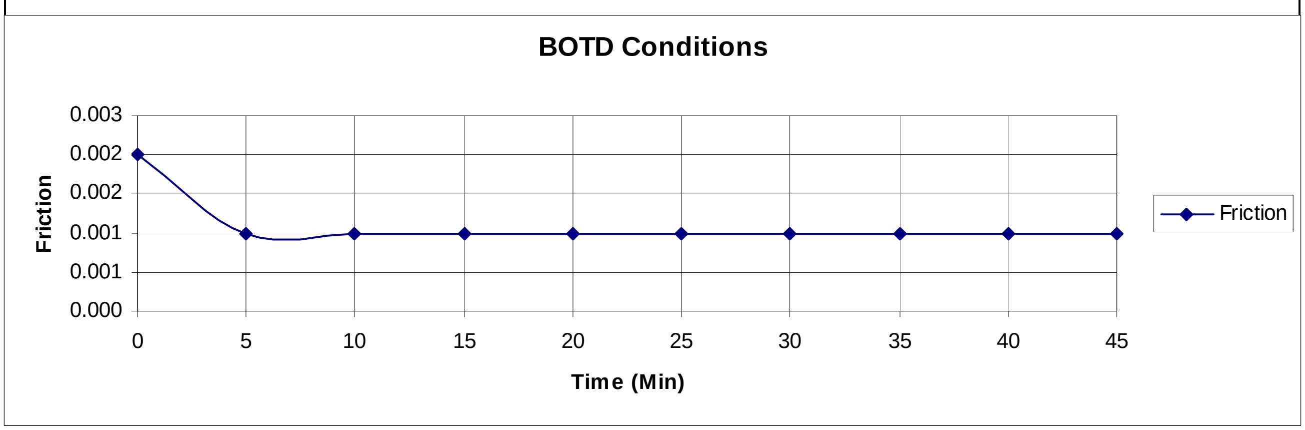




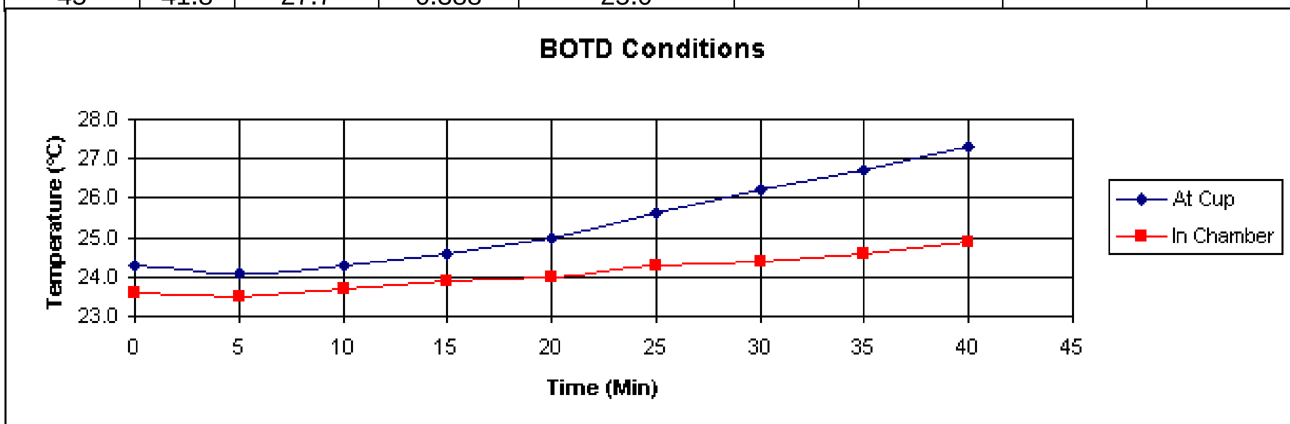
Sample ID:	Fluid B (FL-11762-03)			Run 4, Cup 1 (New)		Date:	8-Aug-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	45.5	25.2	0.002	22.9		µm	µm	µm
5	45.4	25.0	0.001	23.2	Disk 1	624	619	622
10	45.1	25.0	0.001	23.3	Disk 2	619	606	613
15	44.9	25.1	0.001	23.3	Disk 3	627	629	628
20	44.4	25.3	0.001	23.5				
25	44.2	25.5	0.001	23.5	Avg.	621	µm	
30	43.0	25.9	0.001	23.7	Std. Dev.	8	µm	
35	42.6	26.1	0.001	26.1				
40	41.9	26.5	0.001	26.2				
45	41.1	27.0	0.001	26.4				

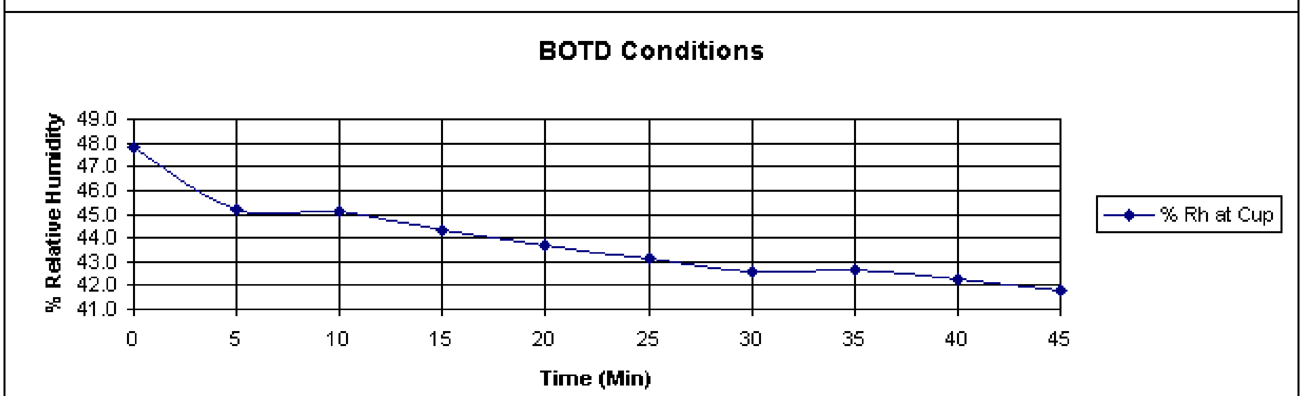


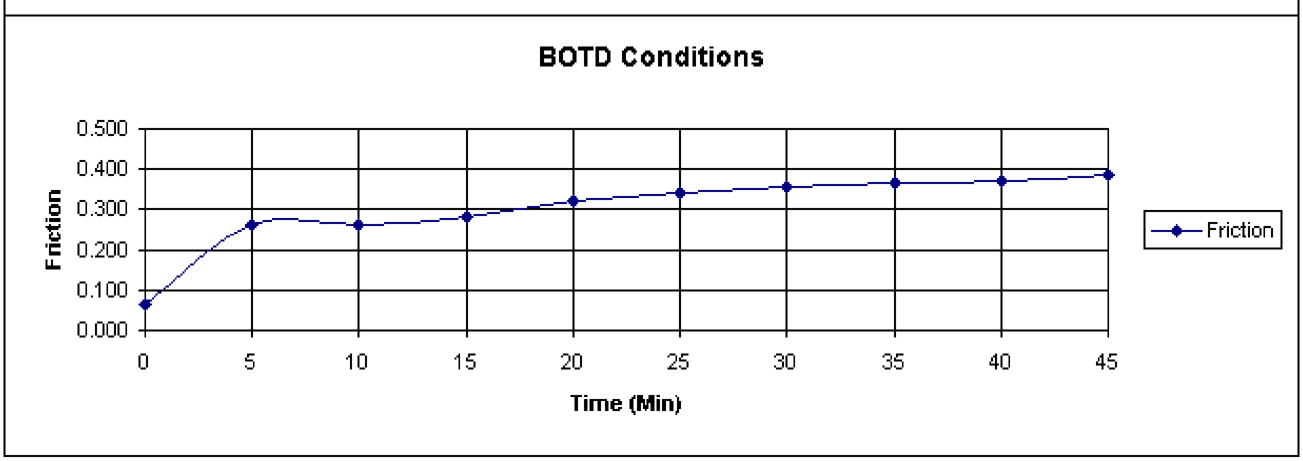




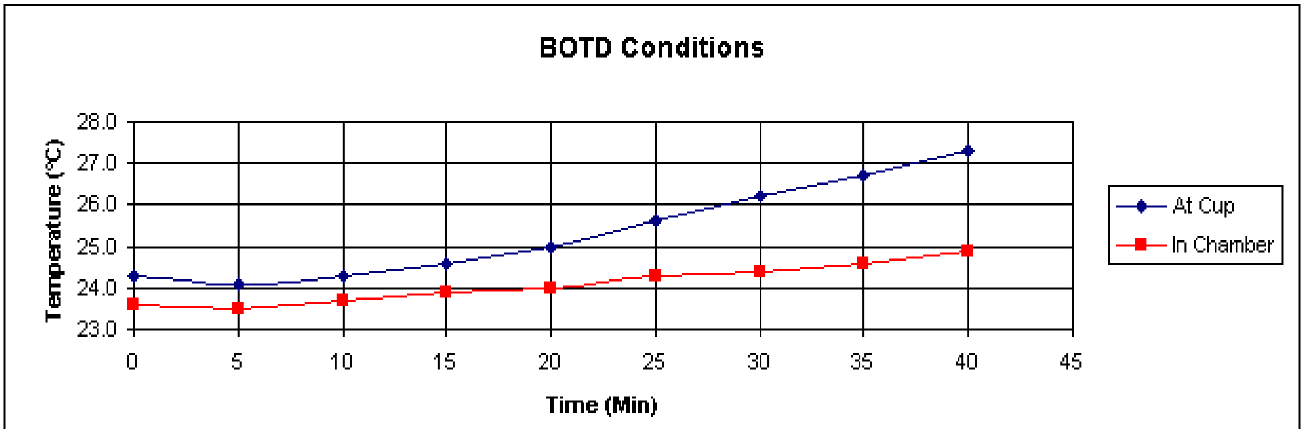
Sample ID:	Fluid B (FL-11762-03)			Run 5, Cup 2		Date:	8-Aug-03	
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**			**Average per Disk**
0	47.8	25.5	0.065	23.6		**µm**	**µm**	**µm**
5	45.2	25.8	0.263	24.1	Disk 1	714	703	709
10	45.1	25.9	0.262	23.9	Disk 2	728	718	723
15	44.3	26.2	0.283	24.0	Disk 3	662	653	658
20	43.7	26.5	0.320	24.2				
25	43.1	26.7	0.340	24.4	**Avg.**	696	**µm**	
30	42.6	27.0	0.356	24.6	**Std. Dev.**	31	**µm**	
35	42.7	27.2	0.367	24.6				
40	42.3	27.4	0.372	24.7				
45	41.8	27.7	0.388	25.0				

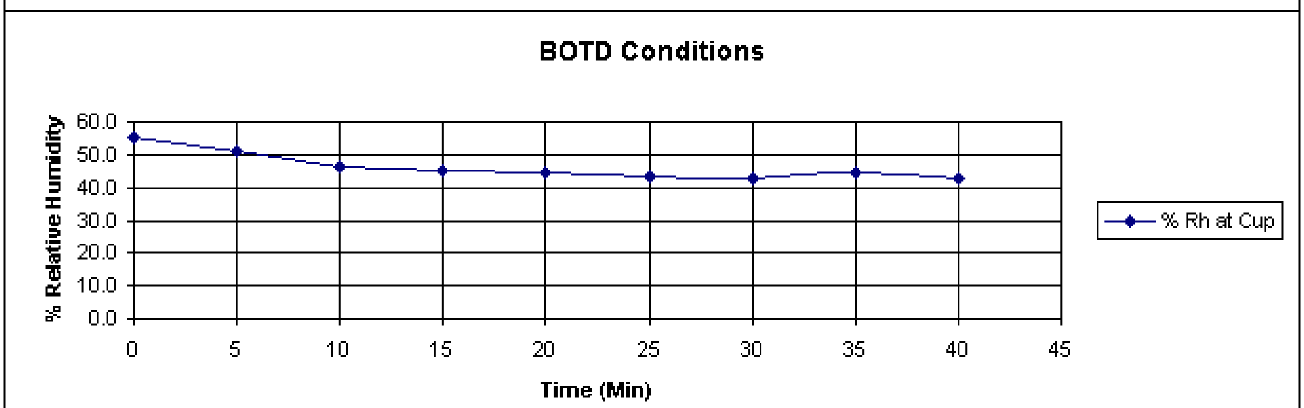


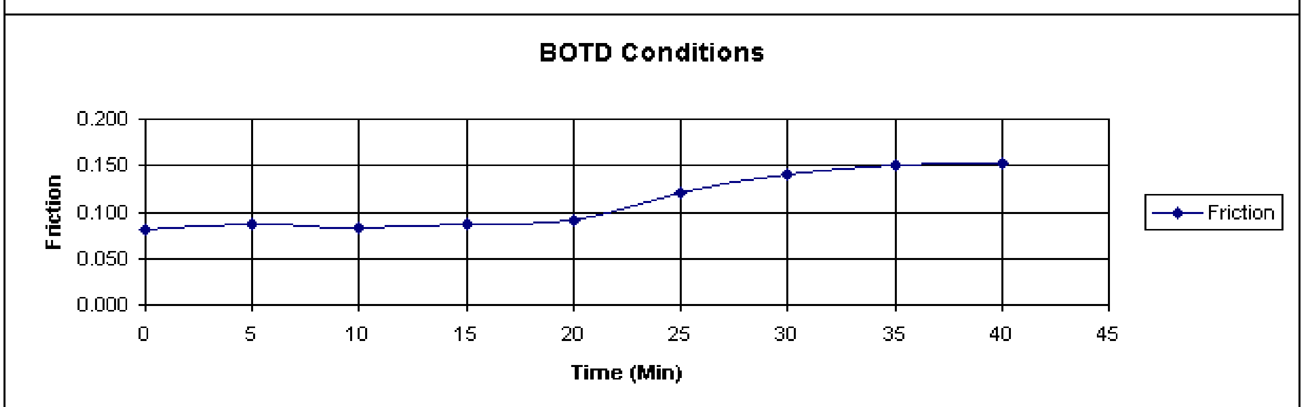




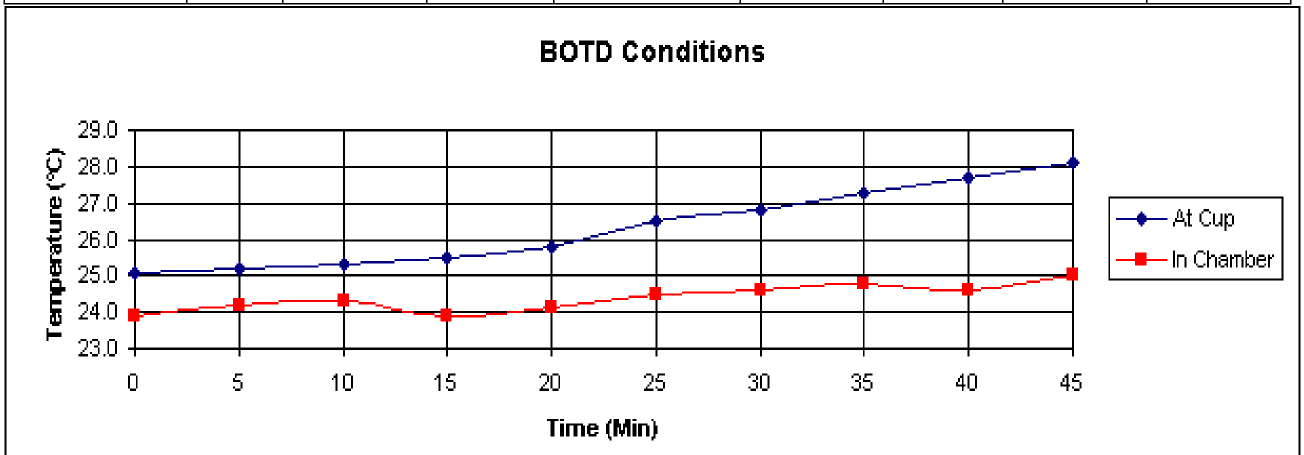
Sample ID:	Fluid B (FL-11762-03)			Run 6, Cup 2		Date:	21-Aug-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	55.5	24.3	0.081	23.6		μm	μm	μm
5	51.3	24.1	0.087	23.5	Disk 1	680	676	678
10	46.3	24.3	0.084	23.7	Disk 2	472	468	470
15	44.9	24.6	0.088	23.9	Disk 3	606	613	610
20	44.5	25.0	0.092	24.0				
25	43.6	25.6	0.120	24.3	Avg.	586	μm	
30	42.7	26.2	0.140	24.4	Std. Dev.	95	μm	
35	44.4	26.7	0.151	24.6				
40	43.0	27.3	0.152	24.9				
45								

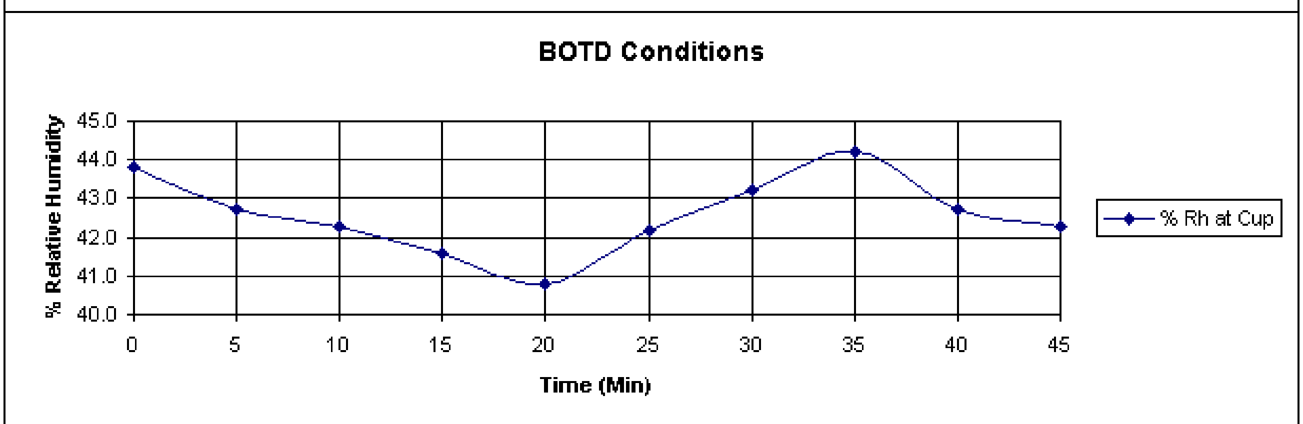


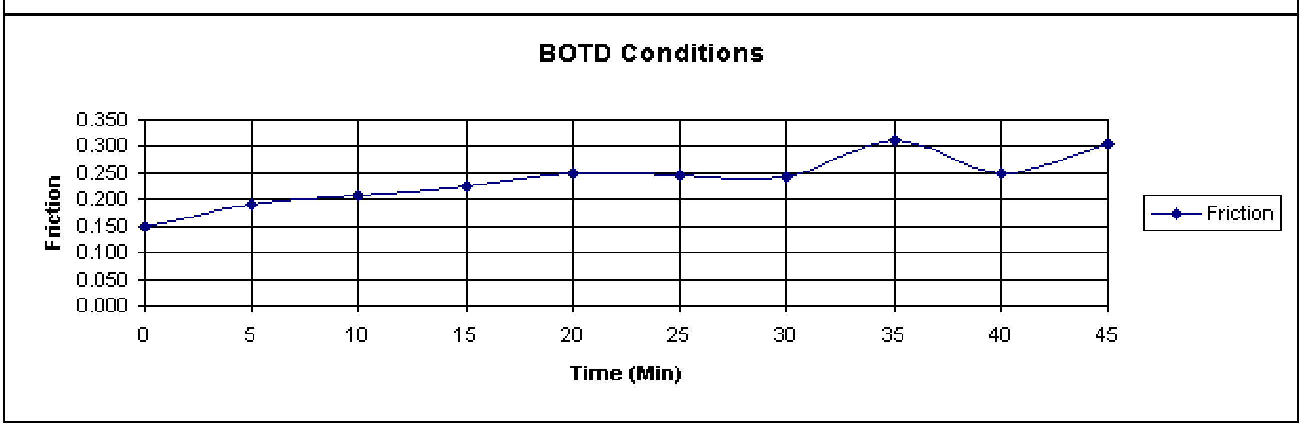




Sample ID:	Fluid B (FL-11762-03)			Run 7, Cup 3		Date:	22-Aug-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	43.8	25.1	0.148	23.9		µm	µm	µm
5	42.7	25.2	0.190	24.2	Disk 1	680	679	680
10	42.3	25.3	0.209	24.3	Disk 2	598	596	597
15	41.6	25.5	0.226	23.9	Disk 3	668	671	670
20	40.8	25.8	0.248	24.1				
25	42.2	26.5	0.245	24.5	Avg.	649	µm	
30	43.2	26.8	0.241	24.6	Std. Dev.	40	µm	
35	44.2	27.3	0.313	24.8				
40	42.7	27.7	0.250	24.6				
45	42.3	28.1	0.306	25.0				



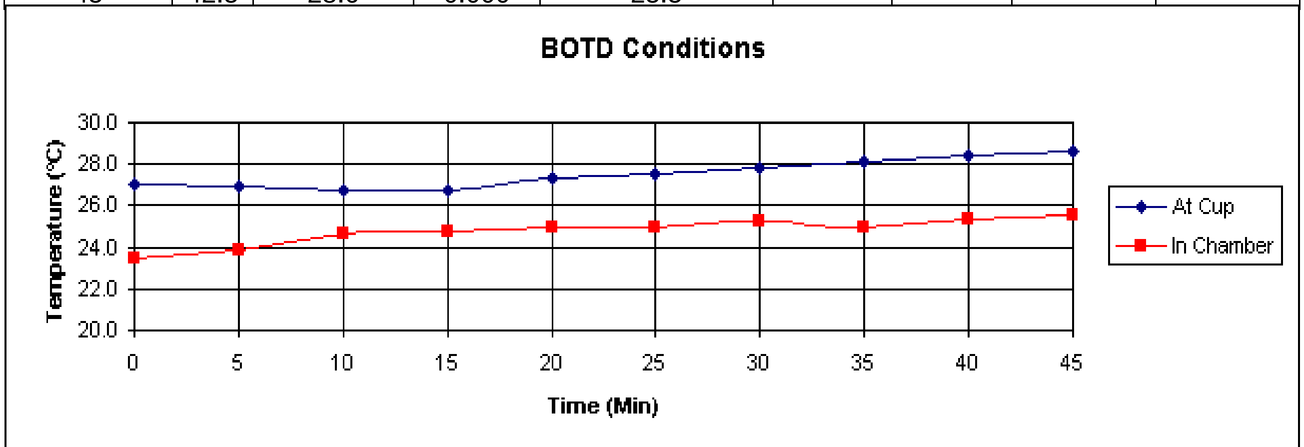


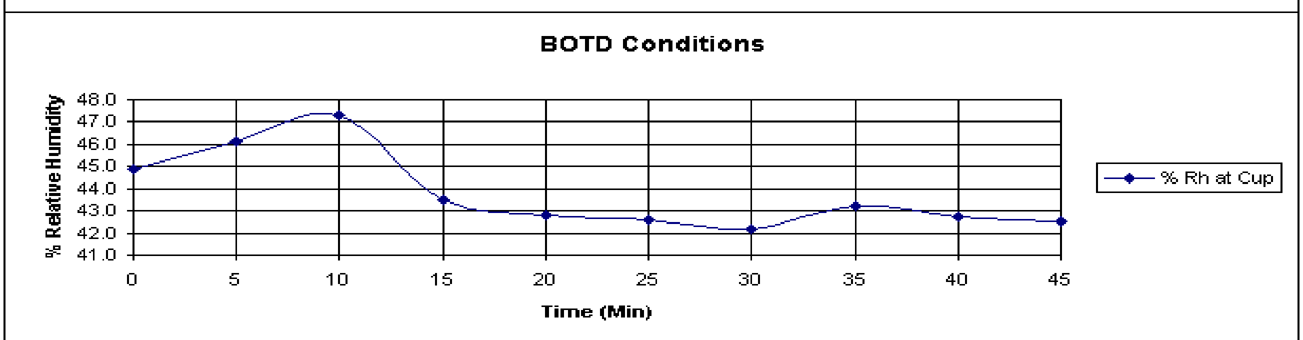


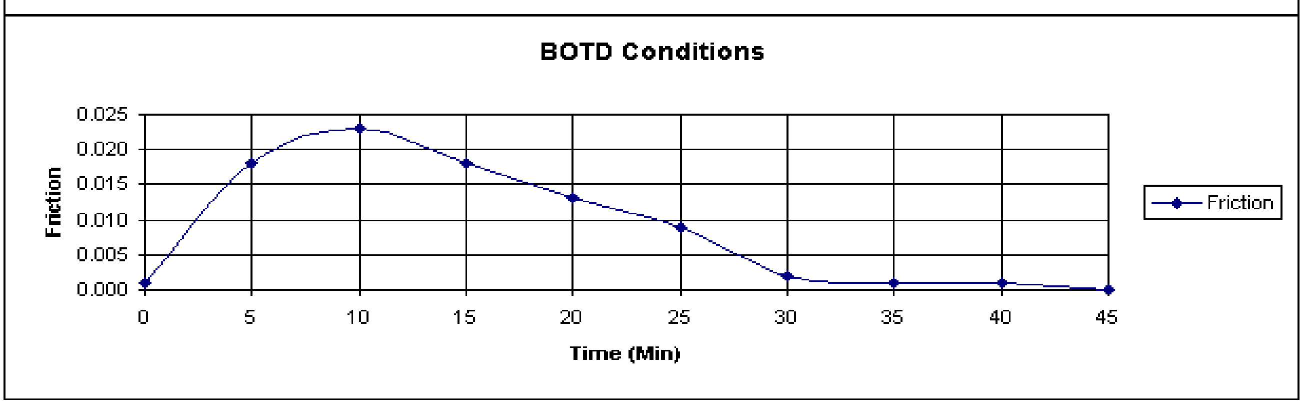
APPENDIX C

Data Sheets for S-5

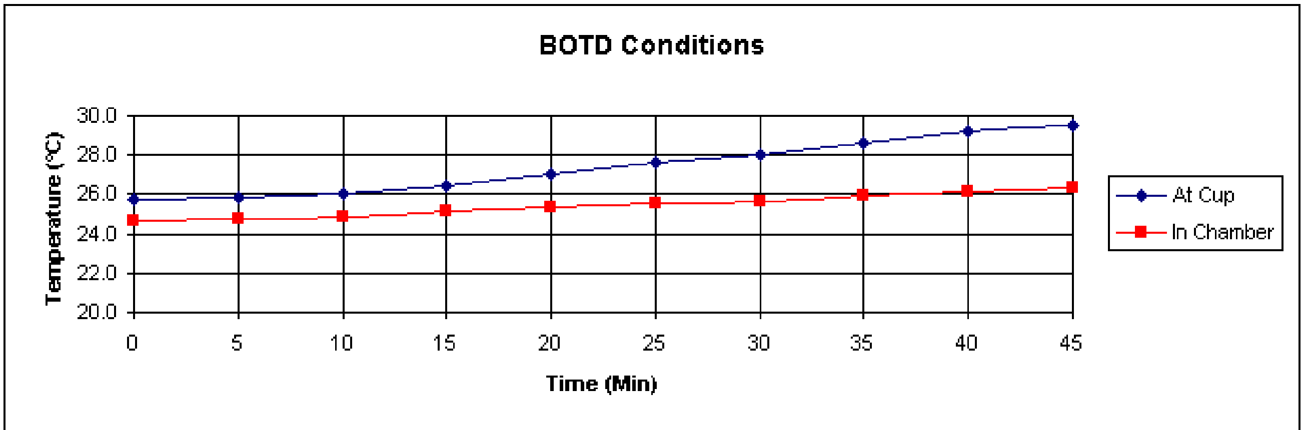
				(New)				
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**			**Average per Disk**
0	44.9	27.0	0.001	23.5		**µm**	**µm**	**µm**
5	46.1	26.9	0.018	23.9	Disk 1	811	809	810
10	47.3	26.7	0.023	24.7	Disk 2	824	818	821
15	43.5	26.7	0.018	24.8	Disk 3	818	809	814
20	42.8	27.3	0.013	25.0				
25	42.6	27.5	0.009	25.0	**Avg.**	815	**µm**	
30	42.2	27.8	0.002	25.2	**Std. Dev.**	6	**µm**	
35	43.2	28.1	0.001	25.0				
40	42.7	28.4	0.001	25.3				
45	42.5	28.6	0.000	25.5				

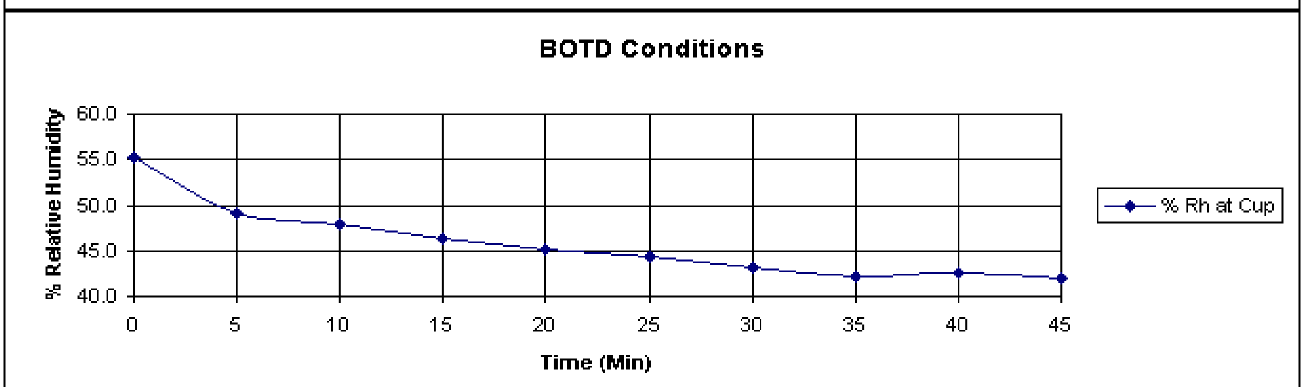


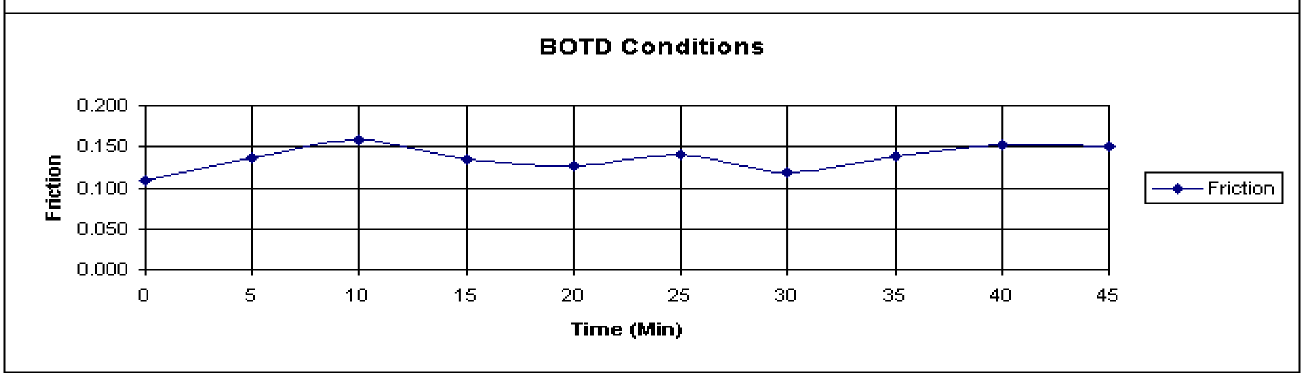




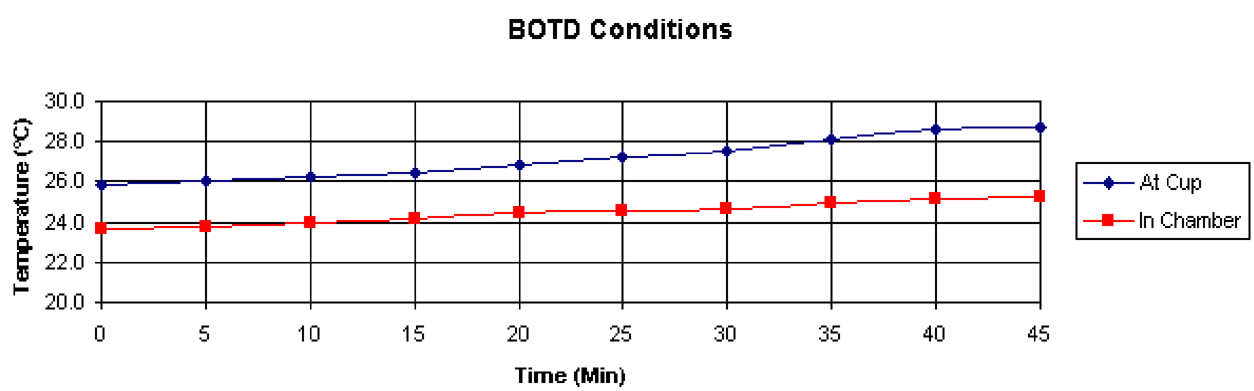
Sample ID:	S5 (FL-11741-03)			Run 2, Cup 3		Date:	13-Aug-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	55.2	25.7	0.108	24.7		µm	µm	µm
5	49.2	25.8	0.137	24.8	Disk 1	701	701	701
10	48.0	26.0	0.158	24.9	Disk 2	817	825	821
15	46.3	26.4	0.135	25.1	Disk 3	701	693	697
20	45.2	27.0	0.127	25.3				
25	44.3	27.6	0.140	25.5	**Avg.**	740	**µm**	
30	43.2	28.0	0.119	25.6	**Std. Dev.**	63	**µm**	
35	42.2	28.6	0.138	25.9				
40	42.6	29.2	0.152	26.1				
45	42.0	29.5	0.150	26.3				

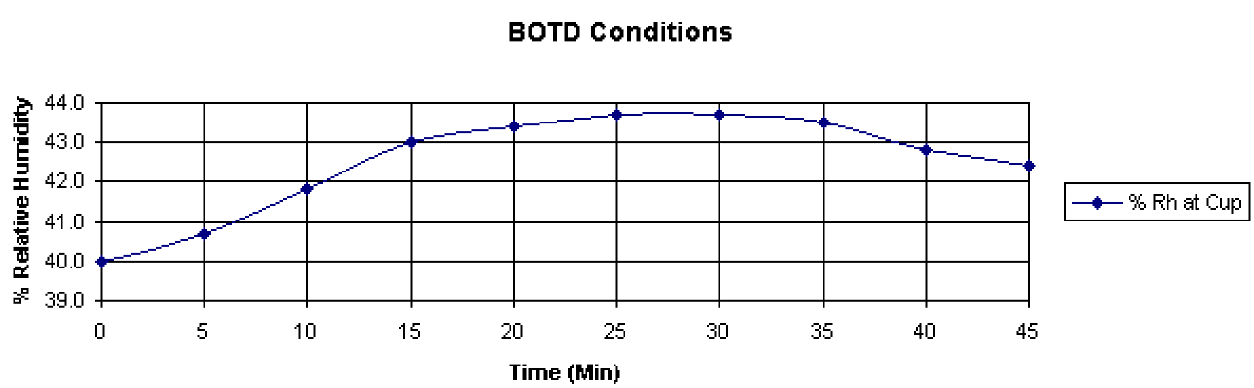


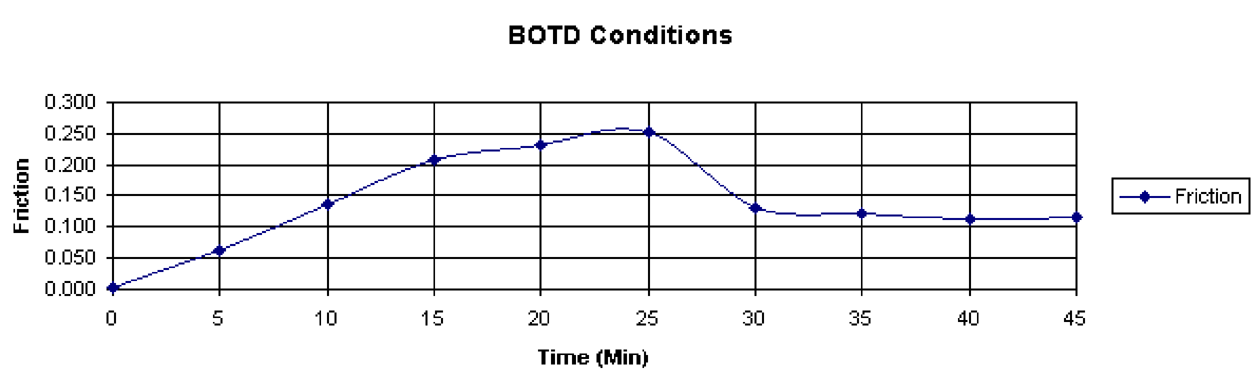




Sample ID:	S5 (FL-11741-03)			Run 3, Cup 1 (New)		Date:	22-Aug-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	40.0	25.8	0.002	23.7		µm	µm	µm
5	40.7	26.0	0.063	23.8	Disk 1	794	794	794
10	41.8	26.2	0.137	24.0	Disk 2	825	821	823
15	43.0	26.4	0.209	24.2	Disk 3	786	790	788
20	43.4	26.8	0.231	24.5				
25	43.7	27.2	0.252	24.6	Avg.	802	µm	
30	43.7	27.5	0.130	24.7	Std. Dev.	17	µm	
35	43.5	28.1	0.121	25.0				
40	42.8	28.6	0.113	25.1				
45	42.4	28.7	0.117	25.2				



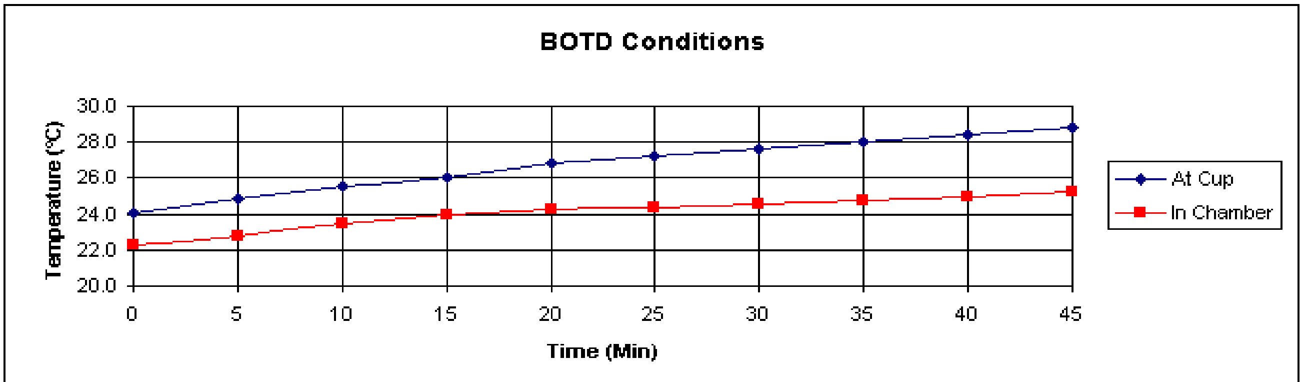


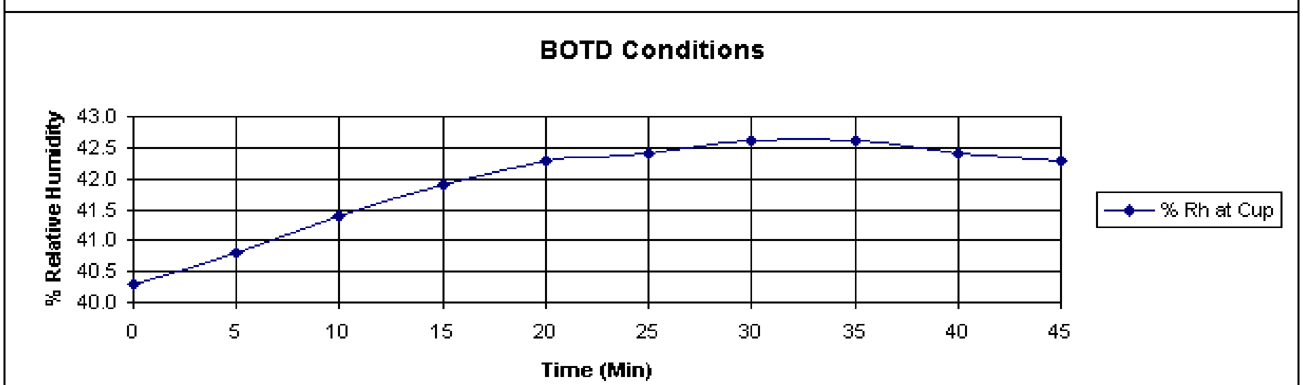


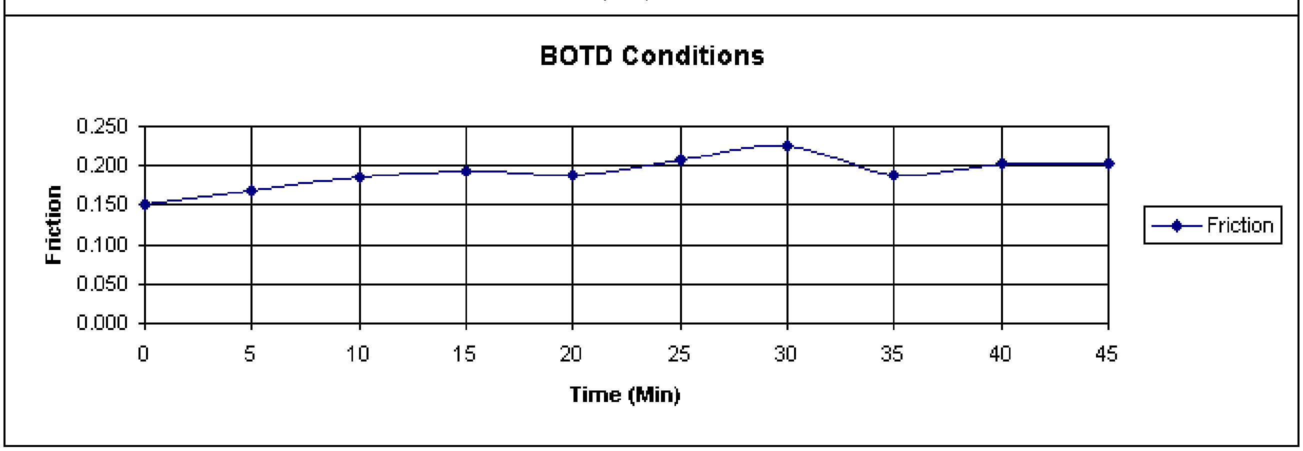
APPENDIX D

Data Sheets for S-5 + 12.0 mg/L CI/LI

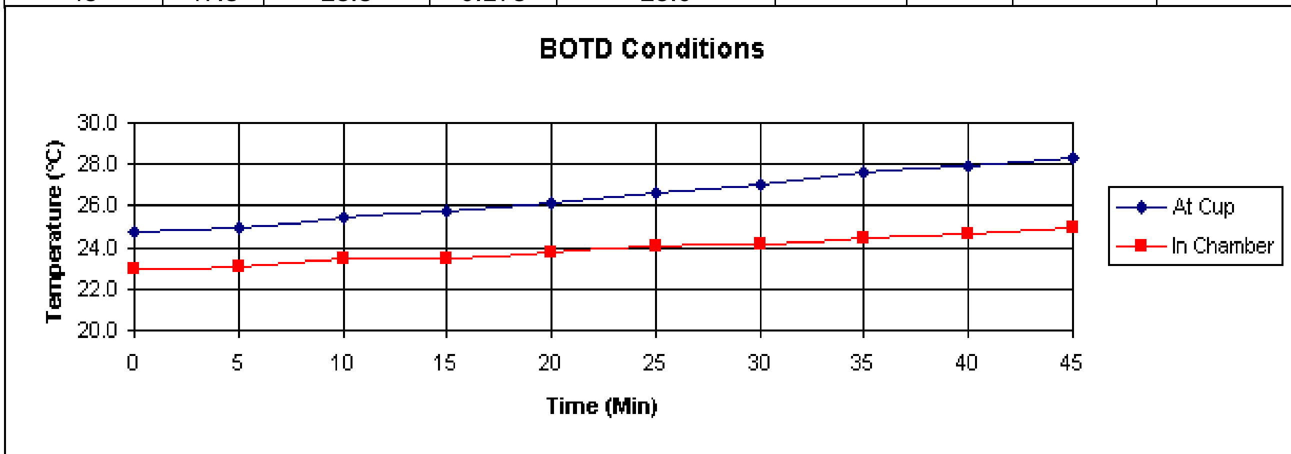
Sample ID:	S5 +12.0 mg/L C.I.			Run 1, Cup 1		Date:	4-Sep-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	40.3	24.1	0.151	22.3		µm	µm	µm
5	40.8	24.9	0.168	22.8	Disk 1	587	587	587
10	41.4	25.5	0.185	23.5	Disk 2	641	635	638
15	41.9	26.0	0.193	24.0	Disk 3	435	432	434
20	42.3	26.8	0.188	24.3				
25	42.4	27.2	0.209	24.4	**Avg.**	553	µm	
30	42.6	27.6	0.226	24.6	**Std. Dev.**	95	µm	
35	42.6	28.0	0.189	24.8				
40	42.4	28.4	0.203	25.0				
45	42.3	28.8	0.202	25.2				

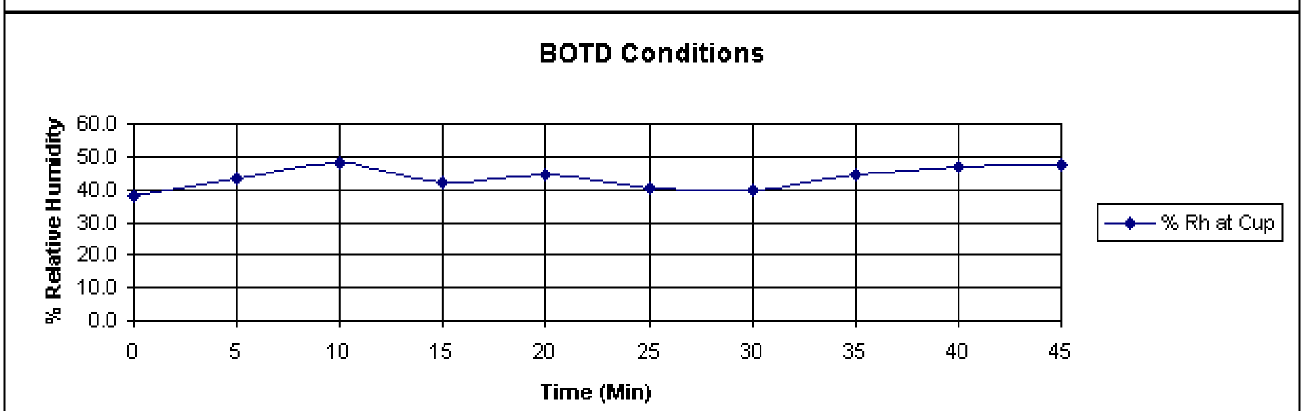


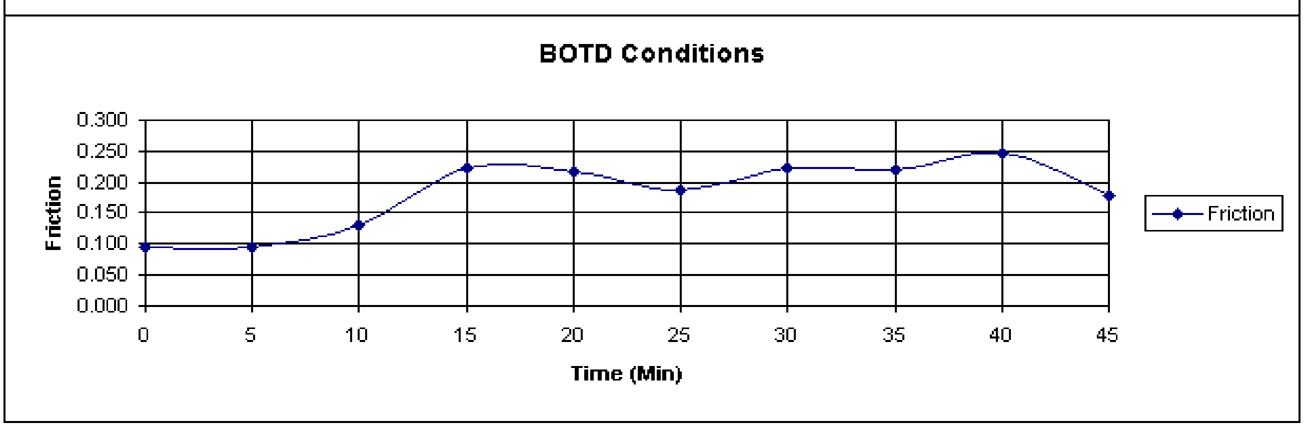




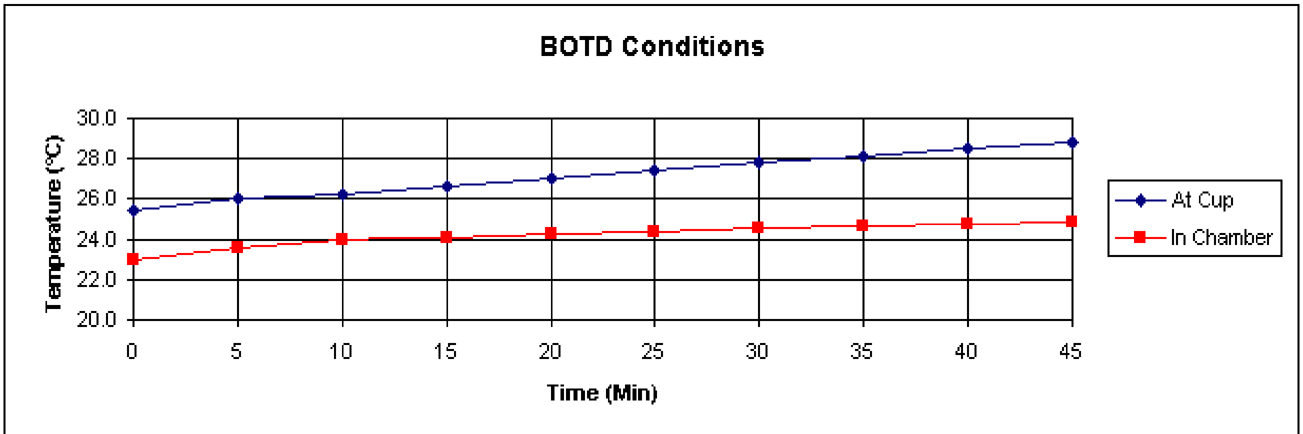
Sample ID:	S5 +12.0 mg/L C.I.			Run 2, Cup 1		Date:	4-Sep-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	37.8	24.8	0.096	23.0		µm	µm	µm
5	43.4	25.0	0.096	23.1	Disk 1	716	722	719
10	48.4	25.4	0.132	23.5	Disk 2	710	704	707
15	41.9	25.7	0.223	23.5	Disk 3	667	670	669
20	44.7	26.1	0.217	23.8				
25	40.1	26.6	0.187	24.1	Avg.	698	µm	
30	40.0	27.0	0.224	24.2	Std. Dev.	24	µm	
35	44.3	27.6	0.221	24.5				
40	46.9	27.9	0.248	24.7				
45	47.8	28.3	0.178	25.0				

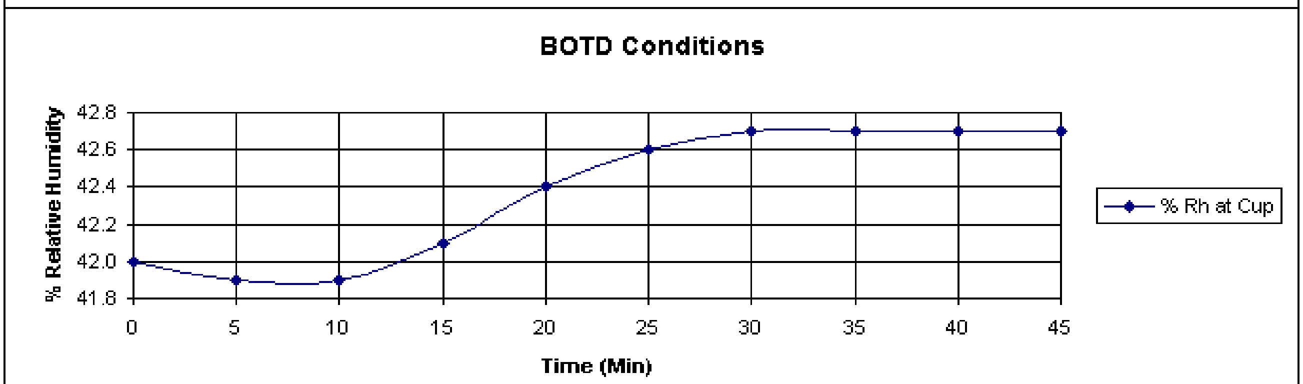


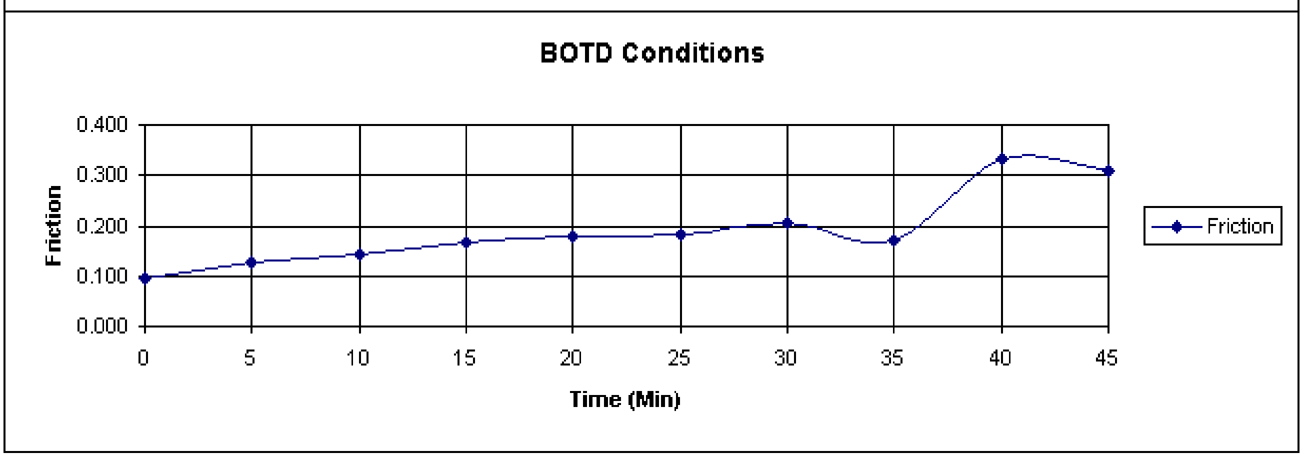




Sample ID:	S5 +12.0 mg/L C.I.		Run 3, Cup 1		Date:	18-Sep-03	
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**		**Average per Disk**
0	42.0	25.4	0.094	23.0		**µm**	**µm**	**µm**
5	41.9	26.0	0.128	23.6	Disk 1	722	719	721
10	41.9	26.2	0.144	24.0	Disk 2	670	675	673
15	42.1	26.6	0.166	24.1	Disk 3	693	697	695
20	42.4	27.0	0.178	24.3				
25	42.6	27.4	0.181	24.4	**Avg.**	696	**µm**	
30	42.7	27.8	0.205	24.6	**Std. Dev.**	22	**µm**	
35	42.7	28.1	0.170	24.7				
40	42.7	28.5	0.334	24.8				
45	42.7	28.8	0.310	24.9				





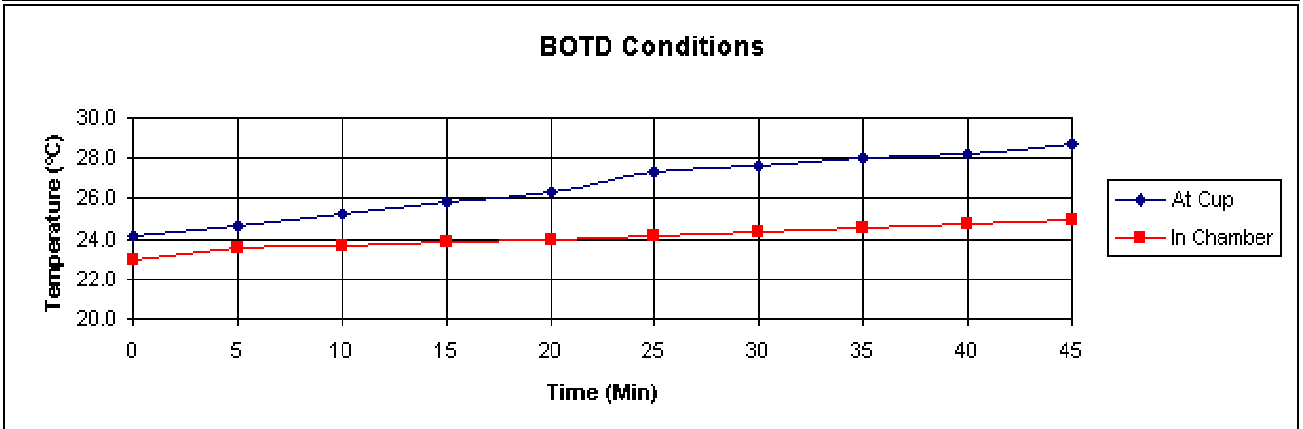


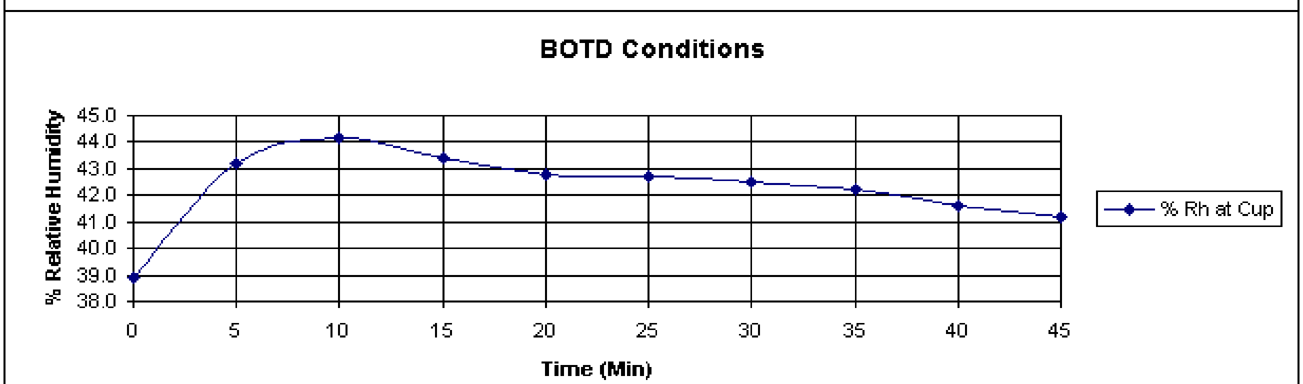
Sample ID:	S5 +22.5 mg/L C.I.		Run 1, Cup 1		**Date:**	28-Aug-03	

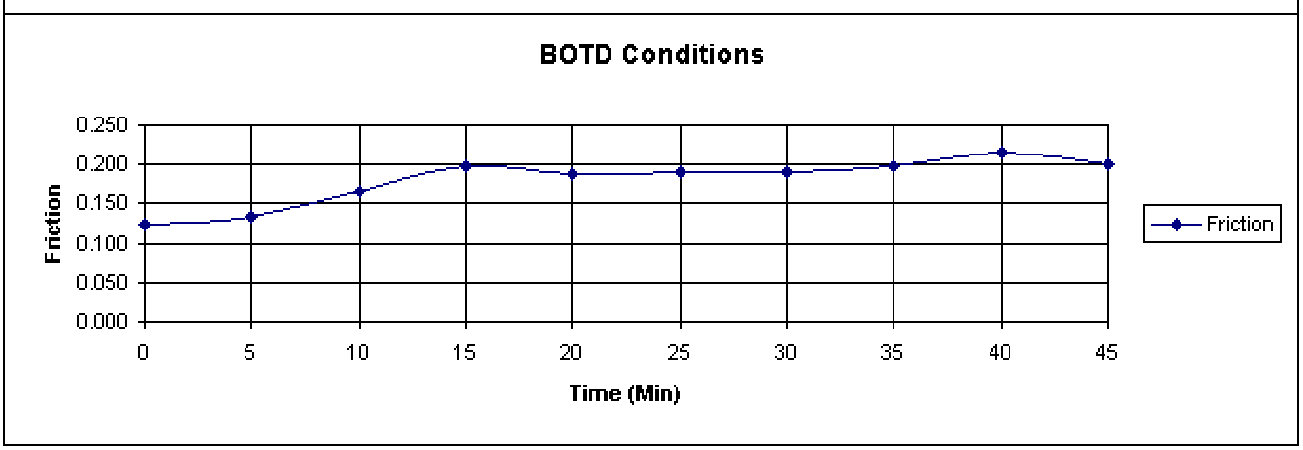
APPENDIX E

Data Sheets for S-5 + 22.5 mg/L CI/LI

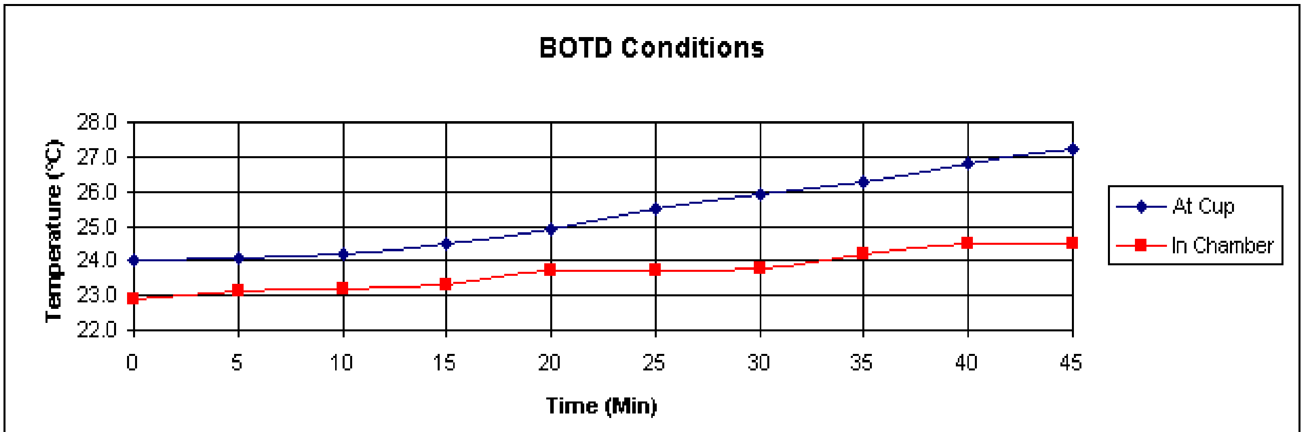
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	38.9	24.2	0.125	23.0		µm	µm	µm
5	43.2	24.7	0.133	23.6	Disk 1	585	587	586
10	44.2	25.2	0.165	23.7	Disk 2	570	569	570
15	43.4	25.8	0.198	23.9	Disk 3	513	516	515
20	42.8	26.3	0.188	24.0				
25	42.7	27.3	0.190	24.2	**Avg.**	557	**µm**	
30	42.5	27.6	0.190	24.4	**Std. Dev.**	34	**µm**	
35	42.2	28.0	0.197	24.6				
40	41.6	28.2	0.215	24.8				
45	41.2	28.7	0.200	25.0				

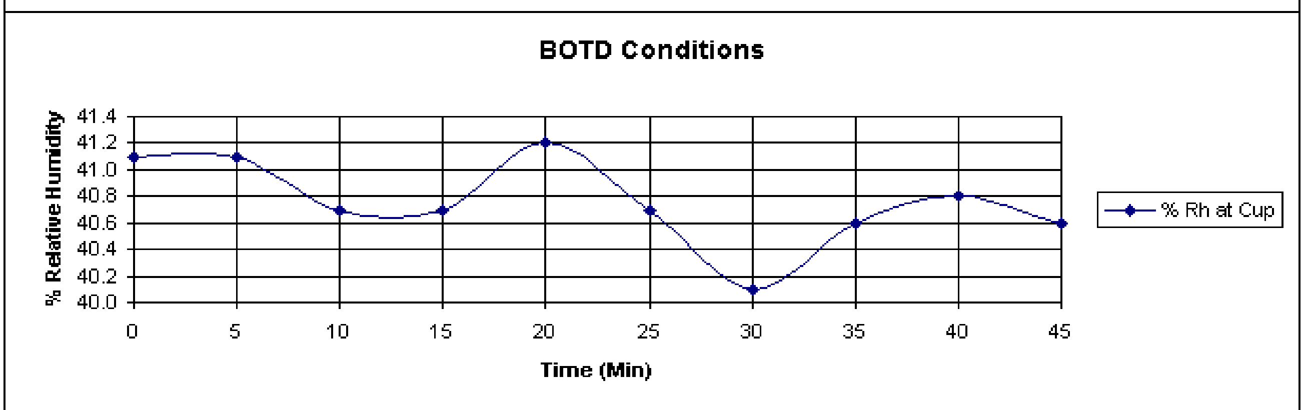


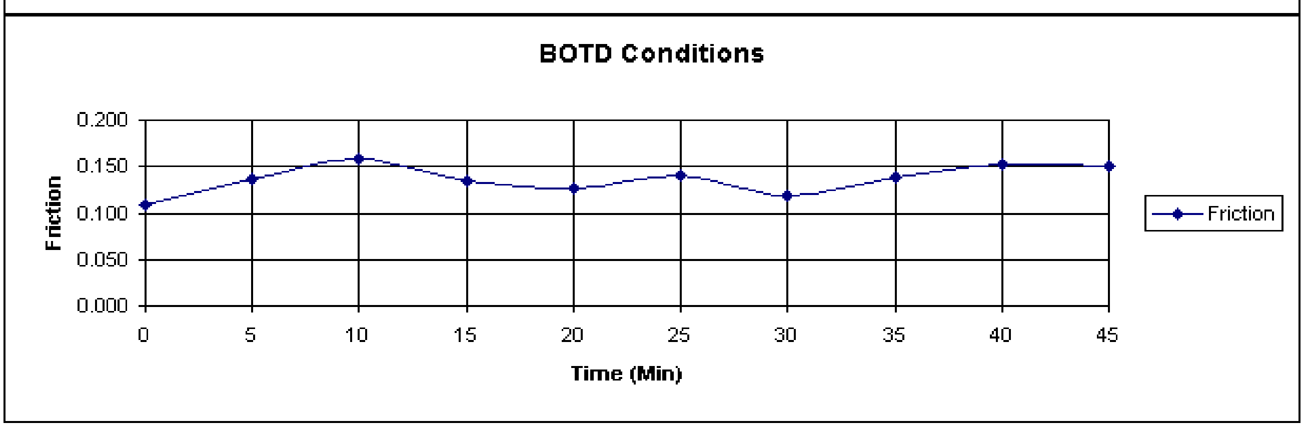




Sample ID:	S5 +22.5 mg/L C.I.			Run 2, Cup 2		**Date:**	2-Sep-03	
Time (Min)	**Rh %**	**@ Temp (°C)**	**Friction**	**Chamber Temp (°C)**	**Disk Measurements**			**Average per Disk**
0	41.1	24.0	0.108	22.9		**µm**	**µm**	**µm**
5	41.1	24.1	0.137	23.1	Disk 1	582	585	584
10	40.7	24.2	0.158	23.2	Disk 2	637	635	636
15	40.7	24.5	0.135	23.3	Disk 3	647	645	646
20	41.2	24.9	0.127	23.7				
25	40.7	25.5	0.140	23.7	**Avg.**	622	**µm**	
30	40.1	25.9	0.119	23.8	**Std. Dev.**	30	**µm**	
35	40.6	26.3	0.138	24.2				
40	40.8	26.8	0.152	24.5				
45	40.6	27.2	0.150	24.5				







Sample ID:	S5 +22.5 mg/L C.I.			Run 3, Cup 1		Date:	3-Sep-03	
Time (Min)	Rh %	@ Temp (°C)	Friction	Chamber Temp (°C)	Disk Measurements			Average per Disk
0	43.0	24.9	0.085	22.8		µm	µm	µm
5	42.5	25.3	0.124	23.3	Disk 1	561	561	561
10	42.3	25.5	0.128	23.6	Disk 2	605	600	603
15	44.1	25.8	0.120	24.0	Disk 3	617	609	613
20	44.7	26.2	0.125	24.1				
25	45.1	26.6	0.128	24.1	Avg.	592	µm	
30	44.4	27.1	0.137	24.1	Std. Dev.	25	µm	
35	44.2	27.7	0.082	24.4				
40	44.3	27.9	0.038	24.7				
45	44.2	28.2	0.042	24.9